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INDUSTRIAL CONTROLS AND TROUBLESHOOTING

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Automation, system of manufacture designed to extend the capacity of machines to perform certain tasks formerly done by humans, and to control sequences of operations without human intervention. The term *automation* has also been used to describe nonmanufacturing systems in which programmed or automatic devices can operate independently or nearly independently of human control. In the fields of communications, aviation, and astronautics, for example, such devices as automatic telephone switching equipment, automatic pilots, and automated guidance and control systems are used to perform various operations much faster or better than could be accomplished by humans.

Elements of Automation

Automated manufacture arose out of the intimate relationship of such economic forces and technical innovations as the division of labor, power transfer and the mechanization of the factory, and the development of transfer machines and feedback systems as explained below.

The division of labor (that is, the reduction of a manufacturing or service process into its smallest independent steps) developed in the latter half of the 18th century and was first discussed by the British economist Adam Smith in his book *An Inquiry into the Nature and Causes of the Wealth of Nations* (1776). In manufacturing, the division of labor results in increased production and a reduction in the level of skills required of workers.

Mechanization was the next step necessary in the development of automation. The simplification of work made possible by the division of labor also made it possible to design and build machines that duplicated the motions of the worker. As the technology of power transfer evolved, these specialized machines were motorized and their production efficiency was improved. The development of power technology also gave rise to the factory system of production, because all workers and machines had to be located near the power source.

The transfer machine is a device used to move a workpiece from one specialized machine tool (*see* MACHINE TOOLS) to another, in such a manner as to properly position the workpiece for the next machining operation. Industrial robots (*see* ROBOT), originally designed only to perform simple tasks in environments dangerous to human workers, are now extremely dexterous and are being used to transfer, manipulate, and index (that is, to position) both light and heavy workpieces, thus performing all the functions of a transfer machine. In actual practice, a number of separate machines are integrated into what may be thought of as one large machine.

In the 1920s the auto industry combined these concepts into an integrated system of production. The goal of this assembly-line system was to make automobiles available to people who previously could not afford them. This method of production was adopted by most automobile manufacturers and rapidly became known as Detroit automation. Despite more recent advances, it is this system of production that most people think of as automation.

Feedback

Essential to all automatic-control mechanisms is the feedback principle, which enables a designer to endow a machine with the capacity for self-correction. A feedback loop is a mechanical, pneumatic, or electronic device that senses or measures a physical quantity such as position, temperature, size, or speed, compares it with a preestablished standard, and takes whatever preprogrammed action is necessary to maintain the measured quantity within the limits of the acceptable standard.

The feedback principle has been used for centuries. An outstanding early example is the flyball

governor, invented in 1788 by the Scottish engineer James Watt to control the speed of the steam engine. In this device a pair of weighted balls is suspended from arms attached to a spindle, which is connected by gears to the output shaft of the engine. At the top of the spindle the arms are linked by a lever with a valve that regulates the steam input. As the engine speeds up beyond the desired rate, causing the spindle to rotate faster, the flyballs are driven upward by centrifugal force. The action of the flyballs partly closes the input valve, reducing the amount of steam delivered to the engine. The common household thermostat is another example of a feedback device.

In manufacturing and production, feedback loops require that acceptable limits or tolerances be established for the process to be performed; that these physical characteristics be measured and compared with the set of limits; and, finally, that the feedback system be capable of correcting the process so that the measured items comply with the standard. Through feedback devices, machines can start, stop, speed up, slow down, count, inspect, test, compare, and measure. These operations are commonly applied to a wide variety of production operations that can include milling, boring, bottling, and refining. *See* CYBERNETICS.

Computer Use

The advent of the computer has greatly facilitated the use of feedback loops in manufacturing processes. Computers and feedback loops have promoted the development of numerically controlled machines (the motions of which are controlled by punched paper or magnetic tapes) and machining centers (machine tools that can perform several different machining operations).

More recently, the introduction of microprocessors and computer combinations have made possible the development of computer-aided design and computer-aided manufacture (CAD and CAM) technology. When using these systems a designer draws a part and indicates its dimensions with the aid of a special light pen on a televisionlike cathode-ray tube computer display screen. After the sketch has been completed to the satisfaction of the designer, the computer automatically generates a magnetic or punched tape that directs a machining center in machining the part. *See* CATHODE RAY TUBE; DRAFTING; MICROPROCESSOR.

Another development that has further increased the use of automation is that of flexible manufacturing systems (FMS). FMS extends automation to companies in which small production runs do not make full automation economically feasible. A computer is used to monitor and govern the entire operation of the factory, from scheduling each step of production to keeping track of parts inventories and tool use.

Automation has also had an influence on areas of the economy other than manufacturing. Small computers are used in systems called word processors, which are rapidly becoming a standard part of the modern office. This technology combines a small computer with a cathode-ray display screen, a typewriter keyboard, and a printer. It is used to edit texts, to type form letters tailored to the recipient, and to manipulate mailing lists and other data. The system is capable of performing many other tasks that increase office productivity. *See* OFFICE SYSTEMS; TYPEWRITER.

Automation in Industry

Many industries are highly automated or use automation technology in some part of their operation. In communications and especially in the telephone industry, dialing, transmission, and billing are all done automatically. Railroads too are controlled by automatic signaling devices, which have sensors that detect cars passing a particular point. In this way the movement and location of trains can be monitored.

Not all industries require the same degree of automation. Agriculture, sales, and some service industries are difficult to automate. The agriculture industry may become more mechanized, especially in the processing and packaging of foods; however, in many service industries such as supermarkets, for example, a checkout counter may be automated and the shelves or supply bins must still be stocked by hand. Similarly, doctors may consult a computer to assist in diagnosis, but they must make the final decision and prescribe therapy.

The concept of automation is evolving rapidly, partly because the applications of automation techniques vary both within a plant or industry and also between industries. The oil and chemical industries, for example, have developed the continuous-flow method of production, owing to the nature of the raw materials used. In a refinery, crude oil enters at one point and flows continuously through pipes in cracking, distillation, and reaction devices as it is being processed into such products as gasoline and fuel oil. An array of automatic-control devices governed by microprocessors and coordinated by a central computer is used to control valves, heaters, and other equipment, thereby regulating both the flow and reaction rates.

In the steel, beverage, and canned food industries, on the other hand, some of the products are produced in batches. For example, a steel furnace is charged (loaded with the ingredients), brought up to heat, and a batch of steel ingots produced. In this phase very little automation is evident. These ingots, however, may then be processed automatically into sheet or structural shapes by being squeezed through a series of rollers until the desired shape is achieved. *See* IRON AND STEEL MANUFACTURE.

The automobile and other consumer product industries use the mass production techniques of step-by-step manufacture and assembly. This technique approximates the continuous-flow concept but involves transfer machines; thus, from the point of view of the auto industry, transfer machines are essential to the definition of automation. *See* AUTOMOBILE INDUSTRY.

Each of these industries uses automated machines in all or part of its manufacturing processes. As a result, each industry has a concept of automation that fits its particular production needs. More examples can be found in almost every phase of commerce. The widespread use of automation and its influence on daily life provides the basis for the concern expressed by many about the influence of automation on society and the individual.

Automation and Society

Automation has made a major contribution toward increases in both free time and real wages enjoyed by most workers in industrialized nations. Automation has greatly increased production and lowered costs, thereby making automobiles, refrigerators, televisions, telephones, and other goods available to more people. It has allowed production and wages to increase, and at the same time the work week has decreased in most Western countries from 60 to 40 hours.

Employment

Not all the results of automation have been positive, however. Some commentators argue that automation has caused overproduction and waste, that it has created alienation among workers, and that it generates unemployment. Of these issues, the relationship between automation and unemployment has received the most attention. Employers and some economists argue that automation has little if any effect on unemployment—that workers are displaced rather than dismissed and are usually employed in another position within the same company or in the same position at another company that has not automated.

Some claim that automation generates more jobs than it displaces. They point out that although some laborers may become unemployed, the industry producing the automated machinery generates more jobs than were eliminated. The computer industry is often cited to illustrate this claim. Business executives would agree that although the computer has replaced many workers, the industry itself has generated more jobs in the manufacturing, sales, and maintenance of computers than the device has eliminated.

On the other hand, some labor leaders and economists argue that automation causes unemployment and, if left unchecked, will breed a vast army of unemployed that could disrupt the entire economy. They contend that growth in government-generated jobs and in service industries has absorbed those who became unemployed due to automation, and that as soon as these areas become saturated or the programs reduced, the true relationship between automation and unemployment will become known.

Automation and the Individual

The effect of automation on the individual has been more drastic. The worker is either displaced or unemployed. Workers who remain must operate or maintain technologically advanced machines, and they may also be required to monitor more of the plant operation and to make on-the-spot decisions. Thus, the education and experience levels of these workers are considerably above those of the workers who were displaced.

Many researchers have described the effect that Detroit automation has on the individual worker as one of alienation. Excessive absenteeism, poor workmanship, and problems of alcoholism, drug addiction, and sabotage of the production lines are well-documented symptoms of this alienation. Many studies have been made since the 1930s, and all conclude that much of the alienation is due to the workers' feelings of being controlled by the machine (because workers must keep pace with the assembly line), boredom caused by repetitious work, and the unchallenging nature of work that requires only a minimum of skill.

The number of workers in more automated industries, especially those using continuous flow processes, tends to be small, and the capital investment in equipment per worker is high. The most dramatic difference between these industries and those using Detroit automation is the reduction in the number of semiskilled workers. It would appear then that automation has little use for unskilled or semiskilled workers, their skills being the most easily replaced by automated devices. The labor force needed in an automated plant consists primarily of such skilled workers as maintenance engineers, electricians, and toolmakers, all of whom are necessary to keep the automated machinery in good operating order.

See also TECHNOLOGY.

Contributed by:
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Further Reading

Electronics, field of engineering and applied physics dealing with the design and application of devices, usually electronic circuits, the operation of which depends on the flow of electrons for the generation, transmission, reception, and storage of information. The information can consist of voice or music (audio signals) in a radio receiver, a picture on a television screen, or numbers and other data in a computer.

Electronic circuits provide different functions to process this information, including amplification of weak signals to a usable level; generation of radio waves; extraction of information, such as the recovery of an audio signal from a radio wave (demodulation); control, such as the superimposition of an audio signal onto radio waves (modulation); and logic operations, such as the electronic processes taking place in computers.

Historical Background

The introduction of vacuum tubes at the beginning of the 20th century was the starting point of the rapid growth of modern electronics. With vacuum tubes the manipulation of signals became possible, which could not be done with the early telegraph and telephone circuit or with the early transmitters using high-voltage sparks to create radio waves. For example, with vacuum tubes weak radio and audio signals could be amplified, and audio signals, such as music or voice, could be superimposed on radio waves. The development of a large variety of tubes designed for specialized functions made possible the swift progress of radio communication technology before World War II and the development of early computers during and shortly after the war.

The transistor, invented in 1948, has now almost completely replaced the vacuum tube in most of its applications. Incorporating an arrangement of semiconductor materials and electrical contacts, the transistor provides the same functions as the vacuum tube but at reduced cost, weight, and power consumption and with higher reliability. Subsequent advances in semiconductor technology, in part attributable to the intensity of research associated with the space-exploration effort, led to the development of the integrated circuit. Integrated circuits may contain hundreds of thousands of transistors on a small piece of material and allow the construction of complex electronic circuits, such as those in microcomputers, audio and video equipment, and communications satellites.

Electronic Components

Electronic circuits consist of interconnections of electronic components. Components are classified into two categories—active or passive. Passive elements never supply more energy than they absorb; active elements can supply more energy than they absorb. Passive components include resistors, capacitors, and inductors. Components considered active include batteries, generators, vacuum tubes, and transistors.

Vacuum Tubes

A vacuum tube consists of an air-evacuated glass envelope that contains several metal electrodes. A simple, two-element tube (diode) consists of a cathode and an anode that is connected to the positive terminal of a power supply. The cathode—a small metal tube heated by a filament—frees electrons , which migrate to the anode—a metal cylinder around the cathode (also called the plate). If an alternating voltage is applied to the anode, electrons will only flow to the anode during the positive half-cycle; during the negative cycle of the alternating voltage, the anode repels the electrons, and no current passes through the tube. Diodes connected in such a way that only the positive half-cycles of an alternating current (AC) are permitted to pass are called rectifier tubes; these are used in the

conversion of alternating current to direct current (DC) (*see* Electricity; Rectification). By inserting a grid, consisting of a spiral of metal wire, between the cathode and the anode and applying a negative voltage to the grid, the flow of electrons can be controlled. When the grid is negative, it repels electrons, and only a fraction of the electrons emitted by the cathode can reach the anode. Such a tube, called a triode, can be used as an amplifier. Small variations in voltage at the grid, such as can be produced by a radio or audio signal, will cause large variations in the flow of electrons from the cathode to the anode and, hence, in the circuitry connected to the anode.

Transistors

Transistors are made from semiconductors. These are materials, such as silicon or germanium, that are "doped" (have minute amounts of foreign elements added) so that either an abundance or a lack of free electrons exists. In the former case, the semiconductor is called n-type, and in the latter case, p-type. By combining n-type and p-type materials, a diode can be produced. When this diode is connected to a battery so that the p-type material is positive and the n-type negative, electrons are repelled from the negative battery terminal and pass unimpeded to the p-region, which lacks electrons. With battery reversed, the electrons arriving in the p-material can pass only with difficulty to the n-material, which is already filled with free electrons, and the current is almost zero.

The bipolar transistor was invented in 1948 as a replacement for the triode vacuum tube. It consists of three layers of doped material, forming two p-n (bipolar) junctions with configurations of p-n-p or n-p-n. One junction is connected to a battery so as to allow current flow (forward bias), and the other junction has a battery connected in the opposite direction (reverse bias). If the current in the forward-biased junction is varied by the addition of a signal, the current in the reverse-biased junction of the transistor will vary accordingly. The principle can be used to construct amplifiers in which a small signal applied to the forward-biased junction causes a large change in current in the reverse-biased junction.

Another type of transistor is the field-effect transistor (FET). Such a transistor operates on the principle of repulsion or attraction of charges due to a superimposed electric field. Amplification of current is accomplished in a manner similar to the grid control of a vacuum tube. Field-effect transistors operate more efficiently than bipolar types, because a large signal can be controlled by a very small amount of energy.

Integrated Circuits

Most integrated circuits are small pieces, or "chips," of silicon, perhaps 2 to 4 sq mm (0.08 to 0.15 sq in) long, in which transistors are fabricated. Photolithography enables the designer to create tens of thousands of transistors on a single chip by proper placement of the many n-type and p-type regions. These are interconnected with very small conducting paths during fabrication to produce complex special-purpose circuits. Such integrated circuits are called monolithic because they are fabricated on a single crystal of silicon. Chips require much less space and power and are cheaper to manufacture than an equivalent circuit built by employing individual transistors.

Resistors

If a battery is connected across a conducting material, a certain amount of current will flow through the material (*see* Resistance). This current is dependent on the voltage of the battery, on the dimensions of the sample, and on the conductivity of the material itself. Resistors with known resistance are used for current control in electronic circuits. The resistors are made from carbon

mixtures, metal films, or resistance wire and have two connecting wires attached. Variable resistors, with an adjustable sliding contact arm, are often used to control volume on radios and television sets.

Capacitors

Capacitors consist of two metal plates that are separated by an insulating material (*see* Capacitor). If a battery is connected to both plates, an electric charge will flow for a short time and accumulate on each plate. If the battery is disconnected, the capacitor retains the charge and the voltage associated with it. Rapidly changing voltages, such as caused by an audio or radio signal, produce larger current flows to and from the plates; the capacitor then functions as a conductor for the changing current. This effect can be used, for example, to separate an audio or radio signal from a direct current in order to connect the output of one amplifier stage to the input of the next amplifier stage.

Inductors

Inductors consist of a conducting wire wound into the form of a coil. When a current passes through the coil, a magnetic field is set up around it that tends to oppose rapid changes in current intensity (*see* Induction). As a capacitor, an inductor can be used to distinguish between rapidly and slowly changing signals. When an inductor is used in conjunction with a capacitor, the voltage in the inductor reaches a maximal value for a specific frequency. This principle is used in a radio receiver, where a specific frequency is selected by a variable capacitor.

Sensing Devices and Transducers

Measurements of mechanical, thermal, electrical, and chemical quantities are made by devices called sensors and transducers. The sensor is responsive to changes in the quantity to be measured, for example, temperature, position, or chemical concentration. The transducer converts such measurements into electrical signals, which, usually amplified, can be fed to instruments for the readout, recording, or control of the measured quantities. Sensors and transducers can operate at locations remote from the observer and in environments unsuitable or impractical for humans.

Some devices act as both sensor and transducer. A thermocouple has two junctions of wires of different metals; these generate a small electric voltage that depends on the temperature difference between the two junctions. A thermistor is a special resistor, the resistance of which varies with temperature. A variable resistor can convert mechanical movement into an electrical signal. Specially designed capacitors are used to measure distance, and photocells are used to detect light (*see* Photoelectric Cell). Other devices are used to measure velocity, acceleration, or fluid flow. In most instances, the electric signal is weak and must be amplified by an electronic circuit.

Power-Supply Circuits

Most electronic equipment requires DC voltages for its operation. These can be provided by batteries (*see* Battery) or by internal power supplies that convert alternating current as available at the home electric outlet, into regulated DC voltages. The first element in an internal DC power supply is a transformer, which steps up or steps down the input voltage to a level suitable for the operation of the equipment. A secondary function of the transformer is to provide electrical ground insulation of the device from the power line to reduce potential shock hazards. The transformer is then followed by a rectifier, normally a diode. In the past, vacuum diodes and a wide variety of different materials such as germanium crystals or cadmium sulfide were employed in the low-power rectifiers used in electronic equipment. Today silicon rectifiers are used almost exclusively because of their low cost and their high reliability.

Fluctuations and ripples superimposed on the rectified DC voltage (noticeable as a hum in a

malfunctioning audio amplifier) can be filtered out by a capacitor; the larger the capacitor, the smaller is the amount of ripple in the voltage. More precise control over voltage levels and ripples can be achieved by a voltage regulator, which also makes the internal voltages independent of fluctuations that may be encountered at an outlet. A simple, often-used voltage regulator is the zener diode. It consists of a solid-state p-n-junction diode, which acts as an insulator up to a predetermined voltage; above that voltage it becomes a conductor that bypasses excess voltages. More sophisticated voltage regulators are usually constructed as integrated circuits.

Amplifier Circuits

Electronic amplifiers are used mainly to increase the voltage, current, or power of a signal. A linear amplifier provides signal amplification with little or no distortion, so that the output is proportional to the input. A nonlinear amplifier may produce a considerable change in the waveform of the signal. Linear amplifiers are used for audio and video signals, whereas nonlinear amplifiers find use in oscillators, power electronics, modulators, mixers, logic circuits, and other applications where an amplitude cutoff is desired. Although vacuum tubes played a major role in amplifiers in the past, today either discrete transistor circuits or integrated circuits are mostly used.

Audio Amplifiers

Audio amplifiers, such as are found in radios, television sets, citizens band (CB) radios, and cassette recorders, are generally operated at frequencies below 20 kilohertz (1 kHz = 1000 cycles/sec). They amplify the electrical signal, which then is converted to sound in a loudspeaker. Operational amplifiers (op-amps), built with integrated circuits and consisting of DC-coupled, multistage, linear amplifiers are popular for audio amplifiers.

Video Amplifiers

Video amplifiers are used mainly for signals with a frequency spectrum range up to 6 megahertz (1 MHz = 1 million cycles/sec). The signal handled by the amplifier becomes the visual information presented on the television screen, with the signal amplitude regulating the brightness of the spot forming the image on the screen. To achieve its function, a video amplifier must operate over a wide band and amplify all frequencies equally and with low distortion. *See* VIDEO RECORDING.

Radio Frequency Amplifiers

These amplifiers boost the signal level of radio or television communication systems. Their frequencies generally range from 100 kHz to 1 GHz (1 billion cycles/sec = 1 gigahertz) and can extend well into the microwave frequency range.

Oscillators

Oscillators generally consist of an amplifier and some type of feedback: The output signal is fed back to the input of the amplifier. The frequency-determining elements may be a tuned inductance-capacitance circuit or a vibrating crystal. Crystal-controlled oscillators offer the highest precision and stability. Oscillators are used to produce audio and radio signals for a wide variety of purposes. For example, simple audio-frequency oscillators are used in modern push-button telephones to transmit data to the central telephone station for dialing. Audio tones generated by oscillators are also found in alarm clocks, radios, electronic organs, computers, and warning systems. High-frequency oscillators are used in communications equipment to provide tuning and signal-detection functions. Radio and television stations use precise high-frequency oscillators to produce transmitting frequencies.

Switching and Timing Circuits

Switching and timing circuits, or logic circuits, form the heart of any device where signals must be selected or combined in a controlled manner. Applications of these circuits include telephone switching, satellite transmissions, and digital computer operations.

Digital logic is a rational process for making simple "true" or "false" decisions based on the rules of Boolean algebra. "True" can be represented by a 1 and "false" by a 0, and in logic circuits the numerals appear as signals of two different voltages. Logic circuits are used to make specific true-false decisions based on the presence of multiple true-false signals at the inputs. The signals may be generated by mechanical switches or by solid-state transducers. Once the input signal has been accepted and conditioned (to remove unwanted electrical signals, or "noise"), it is processed by the digital logic circuits. The various families of digital logic devices, usually integrated circuits, perform a variety of logic functions through logic gates, including "OR," "AND," and "NOT," and combinations of these (such as "NOR," which includes both OR and NOT). One widely used logic family is the transistor-transistor logic (TTL). Another family is the complementary metal oxide semiconductor logic (CMOS), which performs similar functions at very low power levels but at slightly lower operating speeds. Several other, less popular families of logic circuits exist, including the currently obsolete resistor-transistor logic (RTL) and the emitter coupled logic (ELC), the latter used for very-high-speed systems.

The elemental blocks in a logic device are called digital logic gates. An AND gate has two or more inputs and a single output. The output of an AND gate is true only if all the inputs are true. An OR gate has two or more inputs and a single output. The output of an OR gate is true if any one of the inputs is true and is false if all of the inputs are false. An INVERTER has a single input and a single output terminal and can change a true signal to a false signal, thus performing the NOT function. More complicated logic circuits are built up from elementary gates. They include flip-flops (binary switches), counters, comparators, adders, and more complex combinations.

To perform a desired overall function, large numbers of logic elements may be connected in complex circuits. In some cases microprocessors are utilized to perform many of the switching and timing functions of the individual logic elements (*see* Microprocessor). The processors are specifically programmed with individual instructions to perform a given task or tasks. An advantage of microprocessors is that they make possible the performance of different logic functions, depending on the program instructions that are stored. A disadvantage of microprocessors is that normally they operate in a sequential mode, which may be too slow for some applications. In these cases specifically designed logic circuits are used.

Recent Developments

The development of integrated circuits has revolutionized the fields of communications, information handling, and computing. Integrated circuits reduce the size of devices and lower manufacturing and system costs, while at the same time providing high speed and increased reliability. Digital watches, hand-held computers, and electronic games are systems based on microprocessors. Other developments include the digitalization of audio signals, where the frequency and amplitude of an audio signal are coded digitally by appropriate sampling techniques, that is, techniques for measuring the amplitude of the signal at very short intervals. Digitally recorded music shows a fidelity that is not possible using direct-recording methods. Digital playback devices of this nature have already entered the home market. Digital storage could also form the basis of home video systems and may significantly alter library storage systems, because much more information can be stored on a disk for

replay on a television screen than can be contained in a book.

Medical electronics has progressed from computerized axial tomography, or the use of CAT or CT scanners (*see* X RAY), to systems that can discriminate more and more of the organs of the human body. Devices that can view blood vessels and the respiratory system have been developed as well. Ultrahigh definition television also promises to substitute for many photographic processes, because it eliminates the need for silver.

Today's research to increase the speed and capacity of computers concentrates mainly on the improvement of integrated circuit technology and the development of even faster switching components. Very-large-scale integrated (VLSI) circuits that contain several hundred thousand components on a single chip have been developed. Very-high-speed computers are being developed in which semiconductors may be replaced by superconducting circuits using Josephson junctions (*see* JOSEPHSON EFFECT) and operating at temperatures near absolute zero.

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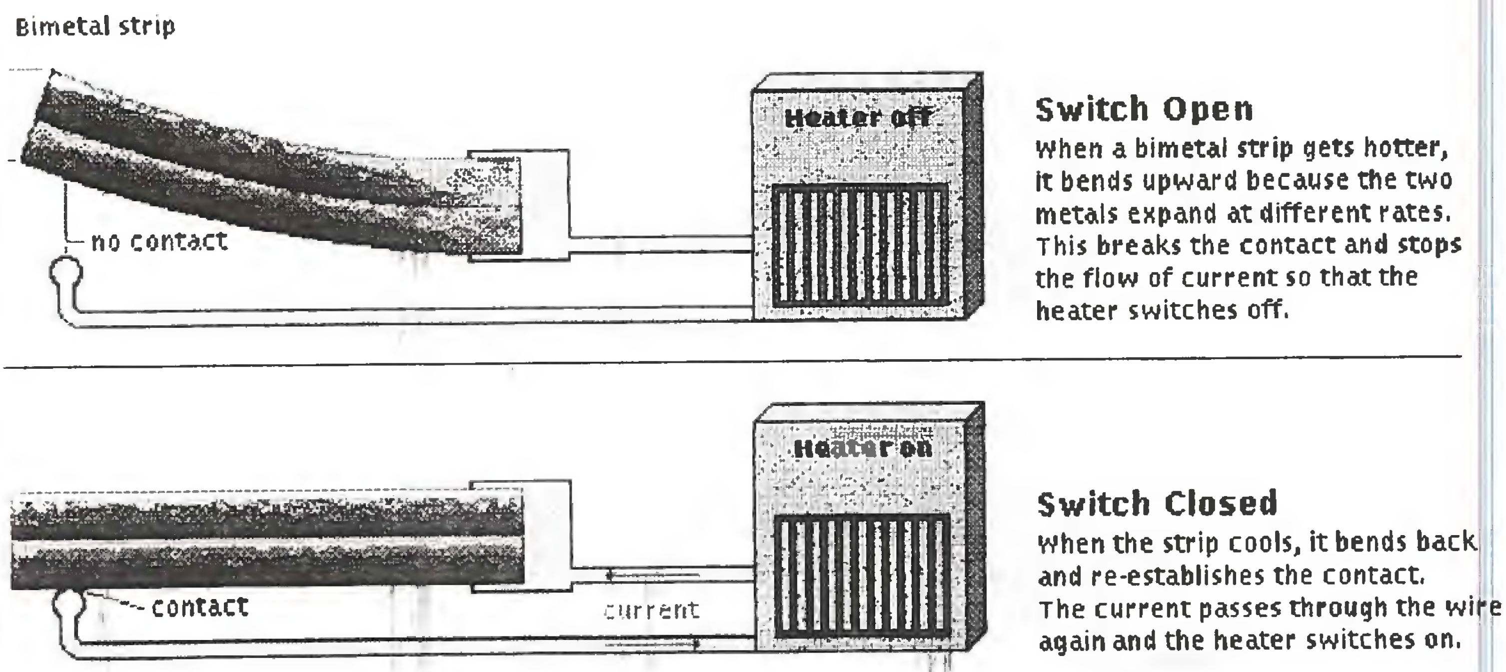
Further Reading

Bimetal Thermostat

A bimetal thermostat uses a special strip of metal to open and close a circuit as temperature fluctuates. Two metals with different expansion rates are bonded to make the strip. The thermostat is arranged so that when the metals are hot, the strip bends upward (toward the metal with the lower expansion rate) and disconnects the circuit. In this particular case, the thermostat will activate a heater when the circuit is closed and electricity is flowing.

Microsoft Illustration



crosoft Illustration

Transformer, electrical device consisting of one coil of wire placed in close proximity to one or more other coils, used to couple two or more alternating-current (AC) circuits together by employing the induction between the coils (*see* ELECTRICITY). The coil connected to the power source is called the primary coil, and the other coils are known as secondaries. A transformer in which the secondary voltage is higher than the primary is called a step-up transformer; if the secondary voltage is less than the primary, the device is known as a step-down transformer. The product of current times voltage is constant in each set of coils, so that in a step-up transformer, the voltage increase in the secondary is accompanied by a corresponding decrease in the current.

Power Transformers

Large devices are used in electric power systems, and small units in electronic devices (*see* ELECTRONICS). Industrial and residential power tranformers that operate at the line frequency (60 Hz in the U.S.), may be single phase or three-phase, and are designed to handle high voltages and currents. Efficient power transmission requires a step-up transformer at the power-generating station to raise voltages, with a corresponding decrease in current. Line power losses are proportional to the square of the current times the resistance of the power line, so that very high voltages and low currents are used for long-distance transmission lines to reduce losses. At the receiving end, step-down transformers reduce the voltage, and increase the current, to the residential or industrial voltage levels, usually 115 to 600 V.

Power transformers must be efficient and should dissipate as little power as possible in the form of heat during the transformation process. Efficiencies are normally above 99 percent and are obtained by using special steel alloys to couple the induced magnetic fields between the primary and secondary windings. The dissipation of even 0.5 percent of the power transmitted in a large transformer generates large amounts of heat, which requires special cooling provisions. Typical power transformers are installed in sealed containers that have oil or another substance circulating through the coils to transfer the heat to external radiatorlike surfaces, where it can be discharged to the surrounding atmosphere.

Electronics

In electronic equipment, transformers with capacities in the order of 1 kw are largely used ahead of a rectifier, which in turn supplies direct current (DC) to the equipment (*see* RECTIFICATION). Such electronic power transformers are usually made of stacks of steel alloy sheets, called laminations, on which copper wire coils are wound. Transformers in the 1- to 100-W power level are used principally as step-down transformers to couple electronic circuits to loudspeakers in radios, television sets, and high-fidelity equipment (*see* SOUND RECORDING AND REPRODUCTION). Known as audio transformers, these devices use only a small fraction of their power rating to deliver program material in the audible ranges, with minimum distortion. The transformers are judged on their ability to reproduce sound-wave frequencies (from 20 Hz to 25 kHz) with minimal distortion over the full sound power level (*see* FREQUENCY; SOUND).

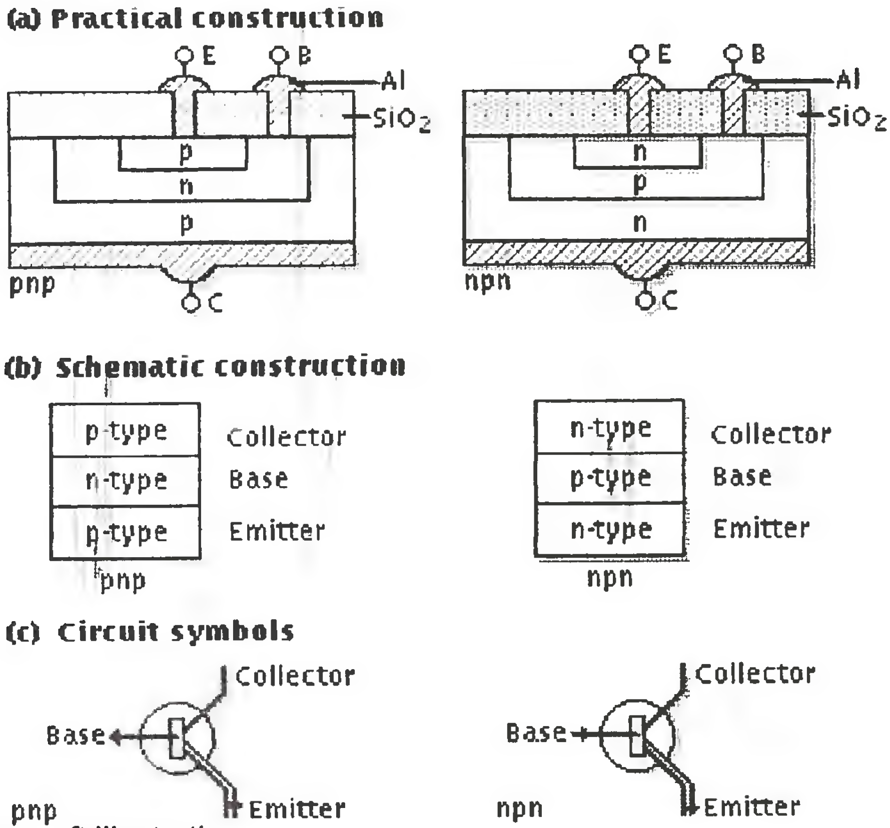
At power levels of 1 milliwatt or less, transformers are primarily used to couple ultrahigh-frequency (UHF), very-high frequency (VHF), radio-frequency (RF), and intermediate-frequency (IF) signals, and to increase their voltage. These high-frequency transformers usually operate in a tuned or resonant circuit (*see* RESONANCE), in which tuning is used to remove unwanted electrical noise at frequencies outside the desired transmission range.

Further Reading

Bipolar Junction Transistors

The bipolar junction transistor consists of three layers of highly purified silicon (or germanium) to which small amounts of boron (p-type) or phosphorus (n-type) have been added. The boundary between each layer forms a junction, which only allows current to flow from p to n. Connections to each layer are made by evaporating aluminum on the surface; the silicon dioxide coating protects the nonmetalized areas. A small current through the base-emitter junction causes a current 10 to 1000 times larger to flow between the collector and emitter. (The arrows show a positive current; the names of layers should not be taken literally.) The many uses of the junction transistor, from sensitive electronic detectors to powerful hi-fi amplifiers, all depend on this current amplification.

Microsoft Illustration



Microsoft Illustration

Thermoelectricity, in physics, electricity generated by the application of heat to the junction of two dissimilar materials. If two wires of different materials are joined at their ends and one end is maintained at a higher temperature than the other, a voltage difference will arise, and an electric current will exist between the hot and the cold junctions. This phenomenon was first observed in 1821 by the German physicist Thomas Seebeck and is known as the Seebeck effect.

For a given combination of materials, the voltage difference varies in direct proportion to the temperature difference. This phenomenon can be utilized for the accurate measurement of temperature by means of a thermocouple in which one wire junction is maintained at a known reference temperature (for example, in an ice bath) and the other at the location where the temperature is to be measured. At moderate temperatures (up to about 260° C/500° F), wire combinations of iron and copper, iron and constantan (a copper-nickel alloy), and copper and constantan are frequently used. At high temperatures (up to 1649° C/3000° F), wires made from platinum and a platinum-rhodium alloy are employed. Because thermocouple wires can be made very small, they also provide a means for the accurate measurement of local spot temperatures. The current can be increased by using semiconductors instead of metals, and a few watts of power can be produced at efficiencies of up to 6 percent (TRANSISTOR). Such thermoelectric converters, powered by kerosene lamps, are widely used in Russia and other republics of the Commonwealth of Independent States to provide power for radio receivers in remote areas.

The inverse effect occurs if current is sent through a circuit made of dissimilar materials, the junctions of which are at the same temperature. In this case, heat will be absorbed at one junction and given up at the other. This phenomenon is known as the Peltier effect for the French physicist Jean Peltier, who discovered it in 1834. Semiconductor systems operating on the Peltier effect can be used as low-powered miniaturized refrigerators for special applications.

Contributed by:
Fred Landis

Thermometer, instrument used to measure temperature. The most commonly used thermometer is the mercury-in-glass type, which consists of a uniform-diameter glass capillary that opens into a mercury-filled bulb at one end. The assembly is sealed to preserve a partial vacuum in the capillary. If the temperature increases, the mercury expands and rises in the capillary. The temperature may then be read on an adjacent scale. Mercury is widely used for measuring ordinary temperatures; alcohol, ether, and other liquids are also employed for this purpose.

The invention of the thermometer is attributed to Galileo, although the sealed thermometer did not come into existence until about 1650. The modern alcohol and mercury thermometers were invented by the German physicist Gabriel Fahrenheit, who also proposed the first widely adopted temperature scale, named after him, in which 32° F is the freezing point of water and 212° F is its boiling point at standard atmospheric pressure. Various temperature scales have been proposed since his time; in the centigrade, or Celsius, scale, devised by the Swedish astronomer Anders Celsius and used in most of the world, the freezing point is 0°, the boiling point is 100°.

Types of Thermometers

A wide variety of devices are employed as thermometers. The primary requirement is that one easily measured property, such as the length of the mercury column, should change markedly and predictably with changes in temperature. The variation of that property should also remain fairly linear with variations in temperature. In other words, a unit change in temperature should lead to a unit change in the property to be measured at all points of the scale.

The electrical resistance of conductors and semiconductors increases with an increase in temperature. This phenomenon is the basis of the resistance thermometer in which a constant voltage, or electric potential, is applied across the thermistor, or sensing element. For a thermistor of a given composition, the measurement of a specific temperature will induce a specific resistance across the thermistor. This resistance can be measured by a galvanometer (*see* ELECTRIC METERS) and becomes a measure of the temperature.

Various thermistors made of oxides of nickel, manganese, or cobalt are used to sense temperatures between -46° and 150° C (between -50° and 300° F). Similarly, thermistors employing other metals or alloys are designed for use at higher temperatures; platinum, for example, can be used up to 930° C (1700° F). With proper circuitry, the current reading can be converted to a direct digital display of the temperature.

Very accurate temperature measurements can be made with thermocouples (*see* THERMOELECTRICITY), in which a small voltage difference (measured in millivolts) arises when two wires of dissimilar metals are joined to form a loop, and the two junctions have different temperatures. To increase the voltage signal, several thermocouples may be connected in series to form a thermopile. Since the voltage depends on the difference of the junction temperatures, one junction must be maintained at a known temperature; otherwise an electronic compensation circuit must be built into the device to measure the actual temperature of the sensor.

Thermistors and thermocouples often have sensing units less than $\frac{1}{4}$ cm (less than $\frac{1}{10}$ in) in length, which permits them to respond rapidly to temperature changes and also makes them ideal for many biological and engineering uses.

The optical pyrometer is used to measure temperatures of solid objects at temperatures above 700° C (about 1300° F), where most other thermometers would melt. At such high temperatures, solid

objects radiate sufficient energy in the visual range to permit optical measurement by exploiting the so-called glow color phenomenon. The color at which hot objects glow changes from dull red through yellow to nearly white at about 1300° C (about 2400° F). The pyrometer contains a light bulb type of filament controlled by a rheostat (dimmer switch) that is calibrated so that the colors at which the filament glows correspond to specific temperatures. The temperature of a glowing object can be measured by viewing the object through the pyrometer and adjusting the rheostat until the filament blends into the image of the object. At this point the temperatures of the filament and the object are equal and can be read from the calibrated rheostat.

Another temperature-measuring device, used mainly in thermostats, relies on the differential thermal expansion between two strips or disks made of different metals and either joined at the ends or bonded together.

Special-Purpose Thermometers

Thermometers may also be designed to register the maximum or minimum temperature attained. A mercury-in-glass clinical thermometer, for example, is a maximum-reading instrument in which a trap in the capillary tube between the bulb and the bottom of the capillary permits the mercury to expand with increasing temperature, but prevents it from flowing back unless it is forced back by vigorous shaking. Maximum temperatures reached during the operation of tools and machines may also be estimated by special paint patches that change color when certain temperatures are reached.

Accuracy of Measurement

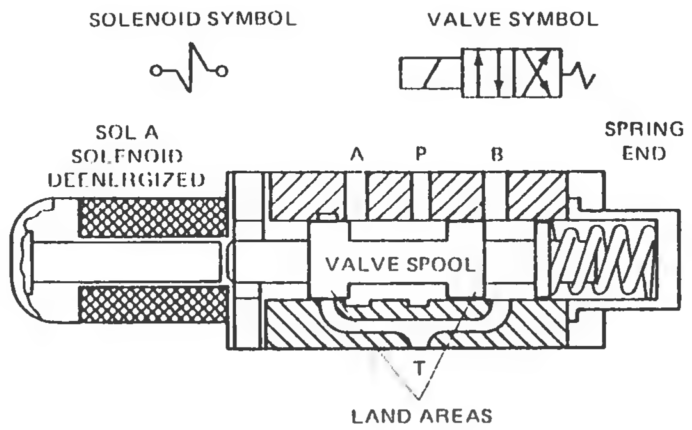
Accurate measurement of temperature depends on the establishment of thermal equilibrium between the thermometric device and its surroundings; that is, when at equilibrium no heat is exchanged between the thermometer and the material it touches or material in its vicinity. A clinical thermometer, therefore, must be inserted long enough (more than one minute) to reach near-equilibrium with the human body to yield an accurate reading. It should also be inserted deep enough, and have sufficient contact with the body, to indicate temperature accurately. These conditions are almost impossible to achieve with an oral thermometer, which generally indicates a body temperature lower than that given by a rectal thermometer. Insertion times can be significantly reduced with small, rapidly reacting thermometers such as thermistor devices.

Any thermometer indicates only its own temperature, which may not agree with the actual temperature of the object to be measured. In measuring the air temperature outside a building, for example, if one thermometer is placed in the shade and one in the sun, only a few centimeters away, the readings on the two instruments may be quite different, although the air temperature is the same. The thermometer in the shade may lose heat by radiation to cold building walls. Its reading, therefore, will be slightly below the true air temperature. On the other hand, the thermometer placed in the sun will absorb the sun's radiant heat. As a result, the indicated temperature may be significantly above the true air temperature. To avoid such errors, accurate temperature determinations require the shielding of the thermometer from hot and cold sources to or from which heat might be transferred by radiation, conduction, or convection.

See HEAT TRANSFER.

Contributed by:
Fred Landis

Further Reading



A.

Figure 5-5

Electromagnet, device consisting of a solenoid (usually a cylindrical coil of insulated wire wound in the form of a helix), in which an iron core is placed. An electric current passed through the coil induces a strong magnetic field along the axis of the helix . When the iron core is placed in this field, microscopic domains that can be considered small permanent magnets in the iron align themselves in the direction of the field, thus increasing greatly the strength of the magnetic field produced by the solenoid. The magnetization of the core reaches saturation once all the domains are completely aligned, and an increase of the current in the solenoid has little further effect. When the current is switched off, the core retains only a weak residual magnetism.

Electromagnets are widely used in technology and are the essential components of relays and circuit breakers (*see* ELECTRIC POWER SYSTEMS). Electromagnets are also used in electromagnetic clutches and brakes. In some streetcars, electromagnetic brakes grip directly onto the rails. Very large electromagnets having cores several meters in diameter are used in cyclotrons (*see* PARTICLE ACCELERATORS), and high-power electromagnets are used to lift iron parts or scrap.

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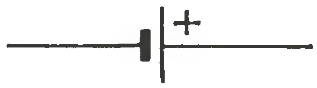
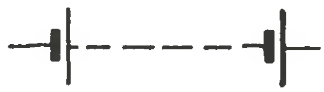
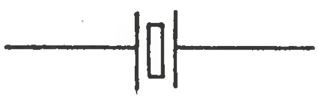
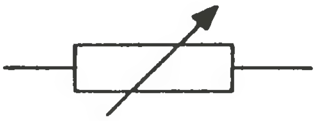
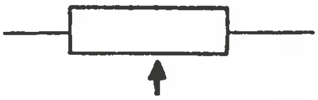
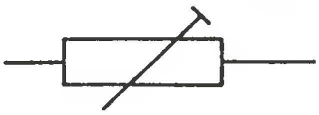
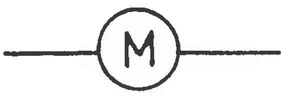
3/2.1

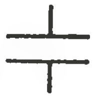
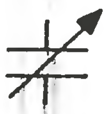
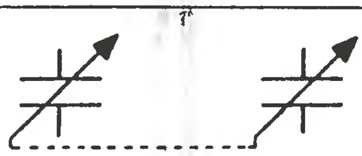
Graphical symbols used in electronics

	Cell
	Battery (several cells in series)
	Fuse (modern symbol)
	Fuse (old symbol)
	Fuse (modern symbol variation)
	Antenna (aerial)
	Quartz crystal
	Coaxial cable (screened cable)

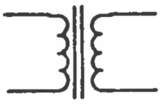
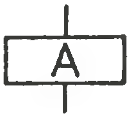
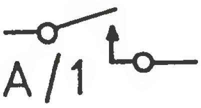
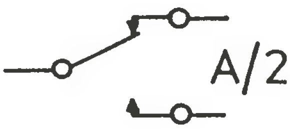
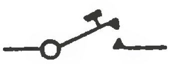
2.1 Graphical symbols used in electronics

	Fixed resistor (modern symbol)
	Fixed resistor (old symbol)
	Fixed resistor, non-inductive
	Variable resistor (modern symbol)
	Variable resistor (old symbol)
	Potentiometer (modern symbol)
	Potentiometer (old symbol)
	Preset resistor (modern symbol)
	Preset resistor (old symbol)
	Motor (if letter is "G" it is a generator)

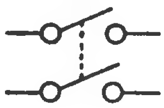
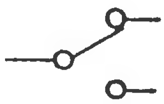
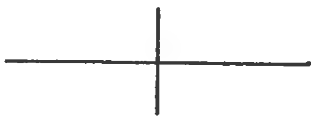
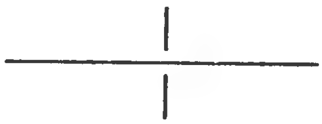
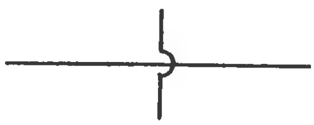
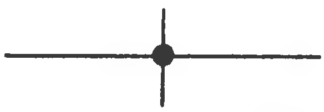
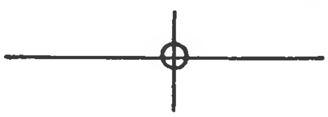
2.1 Graphical symbols used in electronics

	Preset potentiometer (modern symbol)
	Preset potentiometer (old symbol)
	Fixed capacitor
	Fixed capacitor, electrolytic type
	Trimmer or preset capacitor
	Variable capacitor
	Variable capacitors, ganged
	Feed-through capacitor
	Inductor (coil), air cored
	Inductor with ferrite core

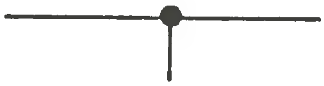
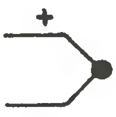
2.1 Graphical symbols used in electronics

	Inductor with metal/iron core
	Inductor with variable ferrite core
	Transformer
	Transformer
	Inductor, air cored
	Inductor, iron cored (choke)
	Relay coil (A)
	Relay contact 1 for relay coil (A) By convention relay contacts shown in rest position
	Relay contact 2 for relay coil (A)
	Morse key

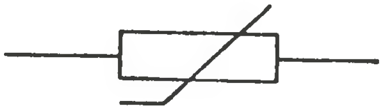
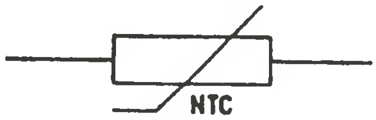
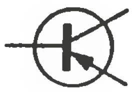
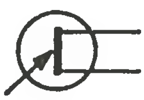
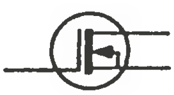
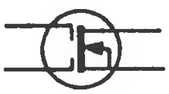
2.1 Graphical symbols used in electronics

	Push to make switch
	Push to break switch
	Toggle switch (Single Pole Single Throw: SPST)
	Toggle switch (Double Pole Single Throw: DPST)
	Toggle switch (Single Pole Double Throw: SPDT)
	Two wires crossing and not connected
	Two wires crossing and not connected
	Two wires crossing and not connected
	Two wires crossing and connected
	Two wires crossing and connected

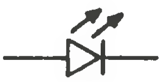
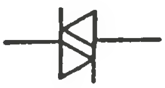
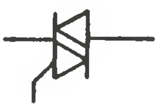
2.1 Graphical symbols used in electronics

	Three wires joined
	Earth
	Chassis
	Supply line (positive or negative)
	Coaxial plug
	Coaxial socket
	Plug
	Socket
	Terminal or terminal pin
	Thermocouple

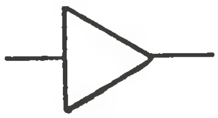
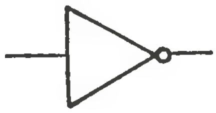
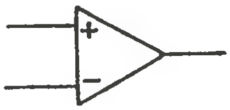
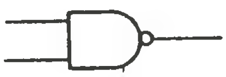
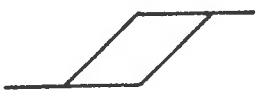
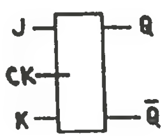
2.1 Graphical symbols used in electronics

	Thermistor (modern symbol)
	Thermistor (old symbol)
	Thermistor with a negative temperature coefficient. PTC shows it is a positive temperature coefficient and V shows it is a voltage dependent resistor
	PNP transistor
	NPN transistor
	P-channel field effect transistor (FET)
	N-channel field effect transistor (FET)
	Unijunction transistor (UJT)
	Single-gate MOS FET
	Dual-gate MOS FET

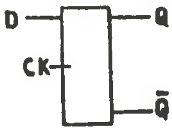
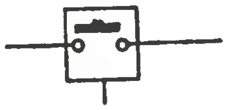
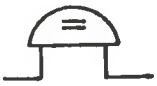
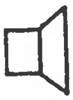
2.1 Graphical symbols used in electronics

	Diode
	Zener diode
	Varicap diode (varactor)
	Light emitting diode (LED)
	Photodiode
	Silicon controlled rectifier (SCR) Also called a thyristor
	Bidirectional breakover diode (diac)
	Bidirectional thyristor (triac)
	Filament lamp
	Neon lamp

2.1 Graphical symbols used in electronics

	Non-inverting amplifier
	Inverting amplifier
	Operational amplifier (op-amp)
	2-input AND gate
	2-input NAND gate (NotAND)
	2-input OR gate
	2-input NOR gate (NotOR)
	2-input EOR gate (ExclusiveOR)
	Schmitt trigger symbol found in Schmitt trigger gates
	JK flipflop

2.1 Graphical symbols used in electronics

	D-type flipflop
	Analogue switch
	Meter (not centre zero)
	Buzzer or bell (alternating current)
	Buzzer or bell (direct current)
	Loudspeaker
	Headphones
	Microphone

3/3.1

Resistance and potentiometers

Resistors determine the flow of current in an electrical circuit. The flow of current is inversely proportional to the resistance: where there is a high resistance, the flow of current is small; where there is a low resistance, the flow of current is large. Resistance, voltage and current are connected in an electrical circuit by Ohm's Law.

$$\boxed{R = \frac{V}{I} \text{ or } I = \frac{V}{R} \text{ or } V = R \cdot I}$$

Conductance $\boxed{G = \frac{1}{R}}$ (Siemens)

The principal parameters for a resistor are:

- Value of resistor (ohm, kohm, Mohm).
- Power rating (watt).
- Resistor tolerance (percentage of the set value).
- Temperature coefficient.

Up to a resistance tolerance of 1% and a power rating of 1 watt, resistors are labelled by a colour code. From 0.5% tolerance and 2 watts rating, the values are given in figures.

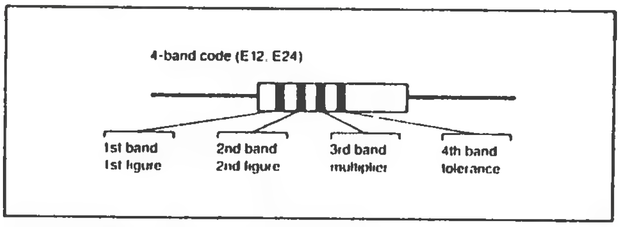


Fig. 3/3.1 a: Tolerance ≥ 5%

Labelling of colour-coded resistors (DIN 41 429)

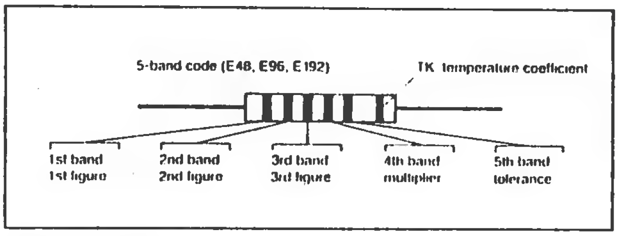


Fig. 3/3.1 b: Tolerance ≤ 2%

Figs. 3/3.1 a & b
Labelling of colour-coded resistors according to IEC 62 and DIN 41 429

Colour codes for resistors according to IEC 62 (DIN 41 429)

Table 3/3.1 c

Colour	Figure	Multiplier		Tolerance
Silver	–	0.01	Ω	10%
Gold	–	0.1	Ω	5%
Black	0	1	Ω	–
Brown	1	10	Ω	1%
Red	2	100	Ω	2%
Orange	3	1	kΩ	–
Yellow	4	10	kΩ	–
Green	5	100	kΩ	0.5%
Blue	6	1	MΩ	0.25%
Violet	7	10	MΩ	0.1%
Grey	8	100	MΩ	–
White	9	–		–

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Examples:

1st band: brown
2nd band: black
4th band: red
5th band: gold

1 kΩ
± 5%

1st band: violet
2nd band: brown
3rd band: green
4th band: red
5th band: brown
6th band: orange

71.5 kΩ
± 1%
15.10⁶/k
(temp. coeff.)

Figure	IEC code
0 10 Ω	R 10
0 33 Ω	R 33
1 0 Ω	1 R 0
1 33 Ω	1 R 33
10 1 Ω	10 R 1
100 Ω	100 R
1 kΩ	1 K 0
10 kΩ	10 K
100 kΩ	100 K
1 0 MΩ	1 M 0
10 MΩ	10 M
100 MΩ	100 M
1 0 GΩ	1 G 0

Table 3/3.1 d: Labelling of resistors in figures and coding according to IEC (right-hand column). The tolerance is printed on the resistor.

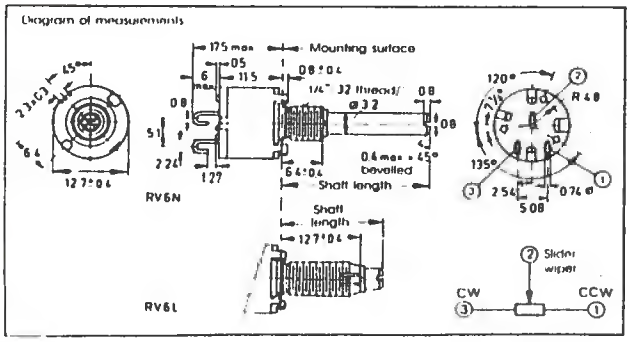


Fig. 3/3.1 e
Dimensions of a 0.5-watt layer potentiometer (variable resistor)

Common types of resistor
(fixed resistors)

- Carbon film/ceramic (normal requirements).
- Carbon film/ceramic (increased demands).
- Carbon film/ceramic (precision resistors).
- Carbon film/ceramic (low drift/high reliability).
- Metal oxide film (forms as above) (heat resistant to 175°C).
- Wire-wound resistors of different constructions for high loads and specialist applications.

Potentiometers or variable resistors

Variable resistors are available both as rheostats and as slide resistors. They operate on the principle of the voltage divider. For small loads there are carbon film resistors (up to about 1 watt); for higher loads, wire-wound resistors.

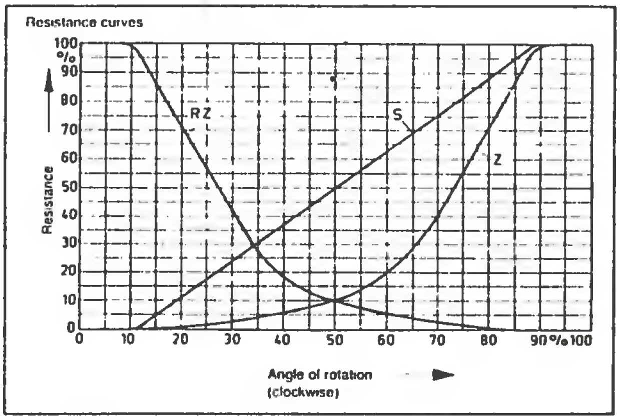


Fig. 3/3.1 f
Variation of resistance as a function of angle of rotation of a potentiometer. Curve S: linear. Curves RZ and Z: logarithmic variations.

3/3.2

Capacitors

Capacitors are electrical energy accumulators which are composed of two metal plates with a dielectric (isolation layer) in between. When a voltage is applied to the metal plates, a flow of electrons takes place. The size of the flow depends upon the voltage applied, the size of the metal plates, the dielectric and the gap between the plates, and appears in the form of a charging current. The three most important determining factors for capacitors are:

- Capacitance C, measured in mF, μF, nF and pF (depending on the size of the plates).
- The maximum operating voltage indicated in volts (depending on the dielectric).
- The polarity, marked on the housing (depending on the construction).

According to the application, the following types are available: fixed capacitors (the capacitance is a fixed size), trimmer capacitors (the capacitance is variable over a small range) or variable capacitors (the capacitance is variable over a larger range). Certain main groups may be distinguished according to the dielectric being used and the rest of the construction:

- Plastic film capacitors (made of metal foil with a plastic film as the dielectric). Paper is hardly ever used as the dielectric these days.
- Ceramic capacitors.
- Electrolytic capacitors (polarised electrodes, high capacity).

The most important formulae for capacitors are:

Capacitors in parallel $$C_{tot} = C_1 + C_2 + C_3 \ldots\ldots + C_n$$

Capacitors in series $$\frac{1}{C_{tot}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \ldots\ldots + \frac{1}{C_n}$$

Capacitive impedance $$X_c = \frac{1}{2 \cdot \pi \cdot f \cdot c} \; [\Omega]$$

Limiting frequency $$f_{lim} = \frac{1}{2 \cdot \pi \cdot R \cdot C} \; [\text{Hz}]$$

3.2 Capacitors

Capacitors are distinguished by size and type and are labelled as follows:

Paper capacitors are labelled with:

- Maker's mark (e.g. Dubilier).
- Type (e.g. MP fDa. . . metallised paper capacitor).
- Rating/tolerance (e.g. 40μF ±10%).
- DIN/IEC or VDE standards (e.g. DIN 41 197).
- Dimensions of casing (e.g. 1 ≙ 48 mm, 2 ≙ 80 mm, 3 ≙ 151 mm).
- Range of operating temperatures (e.g. −20/+40°C).

Small ceramic capacitors are labelled with a combination of symbols and/or colour markings.

Marking of different types of capacitor

Ceramic capacitors

	Tolerance			Rated voltage
B	± 0.1	C⩾10 pF in %	a	50 V DC
C	±0.25		b	125 V DC
D	±0.5	±0.5	c	160 V DC
F	±1.0	±1.1	d	250 V DC
G	±2.0	±2.0	e	350 V DC
H	e.g.	±2.5	g	700 V DC
J	C⩽10 pF	±5.0	h	1000 V DC
K	in pF	±10	u	250 V AC
M		±20	v	350 V AC
P		+100	w	500 V AC
R		+30/−20		
S		+50/−20		
Z		+80/−20		

Example: n 47 Kd

= 0.47 nF, ± 10%, 250 V

Table 3/3.2 a

3.2 Capacitors

Ceramic capacitors with colour coding

Capacity pF	Colour bands from above			Colour of casing
	1st band	2nd band	Multiplier	Tolerance %
Black	–	0	× 1	± 20
Brown	1	1	× 10	–
Red	2	2	× 100	–
Orange	3	3	× 1000	–
Yellow	4	4	× 10000	–
Green	5	5	–	–
Blue	6	6	–	–
Violet	7	7	–	–
Grey	8	8	0.01	–
White	9	9	0.1	± 10

Table 3/3.2 b

Plastic film capacitors

Colour bands			Capacity
1st	2nd	3rd	
Brown	Black	Orange	0.01 μF
Brown	Green	Orange	0.015 μF
Red	Red	Orange	0.022 μF
Orange	Orange	Orange	0.033 μF
Yellow	Violet	Orange	0.047 μF
Blue	Grey	Orange	0.065 μF
Brown	Black	Yellow	0.1 μF
Brown	Green	Yellow	0.15 μF
Red	Red	Yellow	0.22 μF
Orange	Orange	Yellow	0.33 μF
Yellow	Violet	Yellow	0.47 μF
Blue	Grey	Yellow	0.68 μF
Brown	Black	Green	1.00 μF
Brown	Green	Green	1.5 μF
Red	Red	Green	2.2 μF

4th band: tolerance, white ± 10%, black ± 20%
5th band: voltage, red 250 V, yellow 400 V

Table 3/3.2 c

Tantalum electrolytic capacitors

Capacity in μF				
Colour	Top	Band	Spot	Foot-band
Brown	1	1	× 10	–
Red	2	2	× 100	–
Orange	3	3	–	–
Yellow	4	4	–	6.3 V
Green	5	5	–	16 V
Blue	6	6	–	20 V
Violet	7	7	–	20 V
Grey	8	8	× 0.01	25 V
White	9	9	× 0.1	3 V
Black	–	0	× 1	10 V
Pink	–	–	–	35 V

Table 3/3.2 d

3/3.3

Coils/inductances

In simple language coils are wires wound on synthetic mandrels. In electronics they are used for various purposes. As chokes they function in an alternating current circuit like a resistor. In conjunction with a capacitor they form resonant circuits to produce a particular frequency in which an active component is, however, also necessary. Through a series circuit and/or parallel connection of coils and capacitors, frequency filters can be formed which suppress particular frequencies or allow selected frequency bands through. A coil can also serve as a transformer when several windings are wound on one former. There are several different types of coil:

- Air core coil – consisting of the winding and a coreless body; the following formula is used to calculate cylindrical or annular constructions:

$$\boxed{L = \frac{d^2 \cdot N^2 \cdot 10^{-6}}{100 \cdot l + 45 \cdot d}\ [H]}$$

$$\boxed{N = \sqrt{\frac{L \cdot (100 \cdot l + 45 \cdot d)}{d^2 \cdot 10^{-6}}}}$$

N = no. of turns, L = inductance in henry, d = diameter in cm, l = length in cm.

This formula gives a sufficiently precise result if the ratio of the length to the diameter of the coil $\geqslant 5:1$. If the ratio of length to diameter is less than this, then besides the number of turns the height of winding also plays an important part. The following formula applies in this case:

$$\boxed{L = \frac{N^2 \cdot do^2}{h} \cdot 10^{-8}\ [H]}$$

$$\boxed{N = \sqrt{\frac{L \cdot h}{do^2 \cdot 10^{-8}}}}$$

do = median coil diameter in cm,
h = height of winding in cm

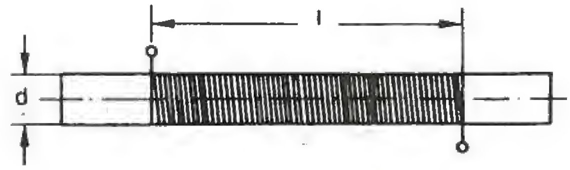


Fig. 3/3.3 a
Air core coil: length/diameter > 5 : 1

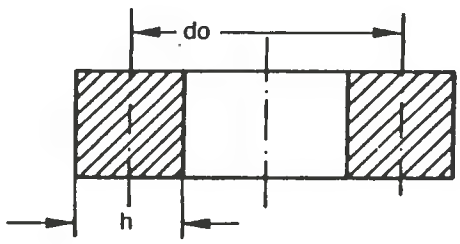


Fig. 3/3.3 b
Air core coil: length/diameter < 1 : 1

3.3 Coils/inductances

Special shapes of air core coil, e.g. comb coils or frame coils, can be calculated only by complicated methods. A further important determining characteristic of coils is the Q factor. It represents the relationship of the reactive component to the active component of the resistance of a coil. The formula for calculating it is:

$$\boxed{g = \frac{N \cdot L}{R_v}}$$

R_v = equivalent resistance (depending on the ohmic resistance, surface: f, eddy current: f_2, and the dielectric: f_3)
f = frequency (Hz)

● Coils with a core have a greater inductance than air core coils and can be tuned more easily. Powdered iron cores have the advantage over solid soft iron cores in that they suffer from smaller eddy current losses. Ferrite (i.e. metal oxide) cores have the added advantage of high permeability relative to that of powdered iron.

Most ferrites are a combination of manganese and zinc oxides or nickel and zinc oxides. They have high Q factors of up to 500 and, because they have a high permeability and low residual magnetism, they can be used up to 600 MHz. Above this frequency, air core coils are usually used.

General coil calculations:

$$\boxed{L = \frac{\mu_0 \cdot \mu_r \cdot A \cdot N^2}{l} \; [H]} \quad \boxed{L = A_l \cdot n^2 \; [H]} \quad \boxed{L = \frac{\Phi \cdot N}{I} \; [H]}$$

μ_0 = magnetic absolute permittivity $1.257 \cdot 10^6$ V_s/A_m
μ_r = permeability figure (dimensionless)
A = cross-section of the magnetic field in m^2
l = average lengths of lines of flux
I = current in amperes (A)
Φ = magnetic flow in webers (Wb), 1 Wb = 1 V_s
A_l = coil constants in V_s/A

Number of turns of coils with cores:

$\boxed{N = K \cdot L}$ (L in mH) $\boxed{N = d \cdot L}$ $\boxed{N = \frac{L}{A_l}}$ (L in nH)

3.3 Coils/inductances

Interconnection of coils in series and parallel:

Series connection: $L_{tot} = L_1 + L_2 + L_3 + \ldots + L_n$

Parallel connection: $\frac{1}{L_{tot}} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \ldots + \frac{1}{L_n}$

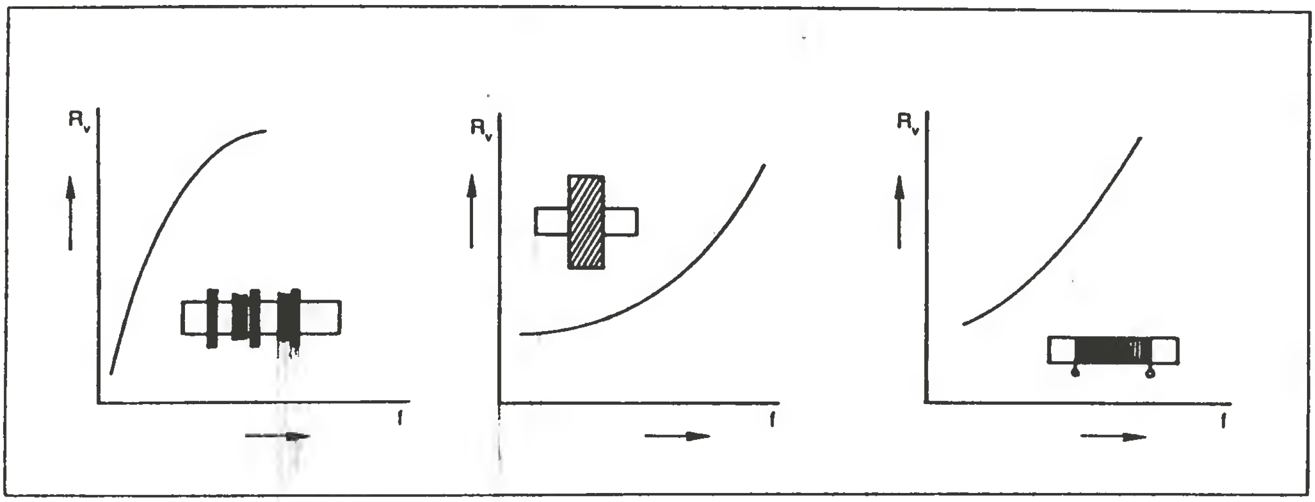


Fig. 3/3.3 c
Resistance R_v of air core coils as a function of the frequency

3/3.4

PTC and NTC resistors

There are two types of thermistor, the PTC resistor and the NTC resistor. The abbreviations come from the descriptions "positive temperature coefficient" and "negative temperature coefficient". A characteristic of these resistors is that from a certain temperature their resistance increases or decreases as the case may be. This temperature is dependent on the material used, and is in the range −40°C to +250°C. The base material can be titanium oxide, barium carbonate or a ceramic oxide. Thermistors are available in metal, glass or plastic cases. PTC resistors are used both as protective elements in circuits and as sensors in measurement and control technology, and NTC resistors are used as temperature sensors for electric thermometers and for temperature compensation in semiconductor circuits.

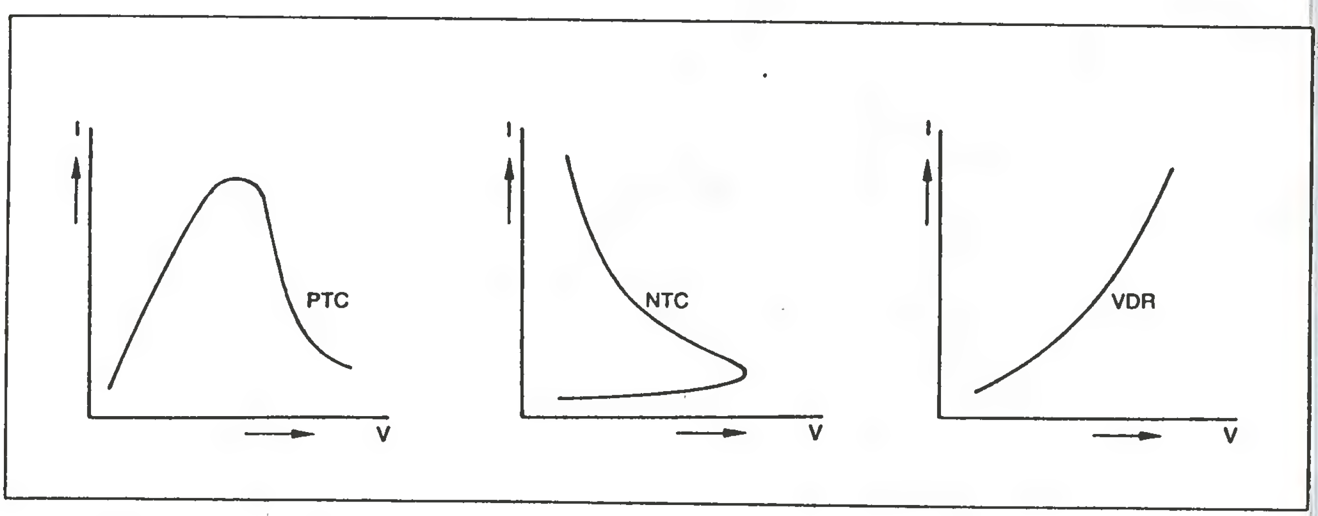


Fig. 3/3.4 a
Characteristic curves of PTC, NTC and VDR resistors (varistors) (I/V)

38

.4 PTC and NTC resistors

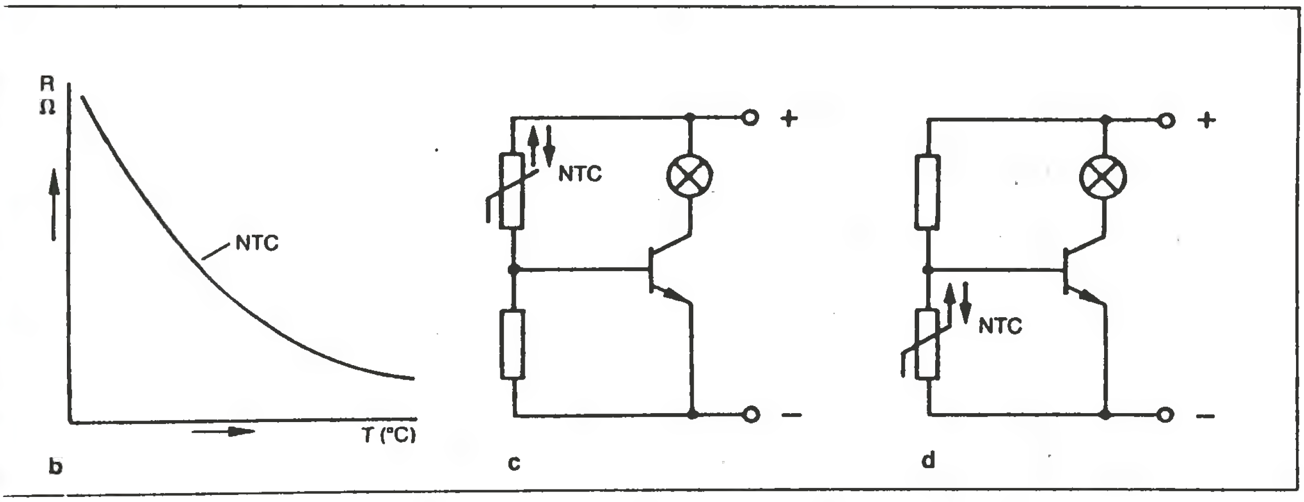


Fig. 3/3.4 b
Resistance as a function of temperature in an NTC resistor

Fig. 3/3.4 c

Fig. 3/3.4 d

c) Thermistors in a transistor circuit:
Collector current increases (lamp lights up) when the temperature of the NTC resistor increases.
d) Collector current increases when the temperature decreases.

3/3.5

Varistors (VDR resistors)

The varistor is a resistor the resistance of which varies with voltage (VDR stands for voltage dependent resistor). The resistance is high at low voltage and decreases with increasing voltage. Varistors are used to protect components which are sensitive to excess voltage. The base material of earlier varistors was often sintered silicon carbide which achieved its resistance variation by the alteration of the contact resistance of the silicon carbide crystals with voltage. This type has been largely superseded by zinc oxide varistors which have a superior response when compared with silicon carbide varistors.

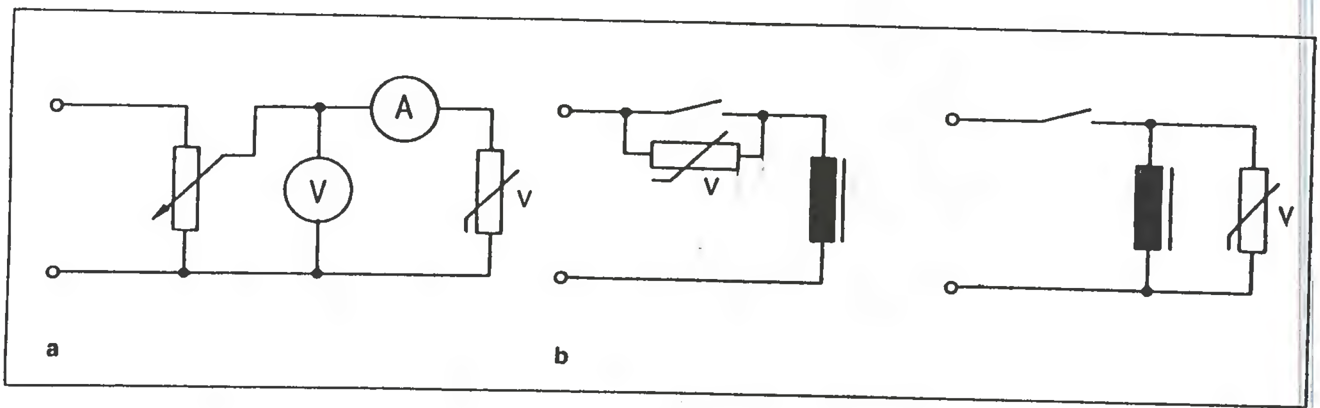


Fig. 3/3.5 a
Measuring circuit for varistor

Fig. 3/3.5 b
Varistor used as a contact protector for circuits with inductive load

3/3.6

Diodes/Zener diodes

Diodes are semiconductor components with the ability to conduct in only one direction (the forward direction). This property of the diode is due to the movement of the charge carriers in the junction between two semiconducting zones which are doped separately. The p zone constitutes the anode; the n zone is the cathode. Usually the cathode is marked with a ring, dot or other marking on the casing. The base material is germanium or silicon. Diodes are distinguished as follows:

1st letter	2nd letter	3rd letter	Type number
A = Germanium diode B = Silicon diode	A = All purpose B = Capacitive- P = Photo- Q = Light- Y = Rectifier- Z = Zener diode	Labelling for increased requirements, e.g. for industrial use	113 116 117 118 or others

Important parameters for diodes (see Chapter 6/2):

- Reverse voltage V_R (max.). Exceeding this leads to conduction in reverse direction.
- Forward voltage V_F. Threshold of the current flow in forward direction (Si diodes 0.6 to 0.7 V).
- Forward current I_F.
- Power dissipation P_{tot}, product of $V_F \cdot I_F$; this is the carrying capacity of the diode.
- Reverse current I_R. Undesirable leakage current.
- Thermal resistance R_{th}, essential for the loading capacity.

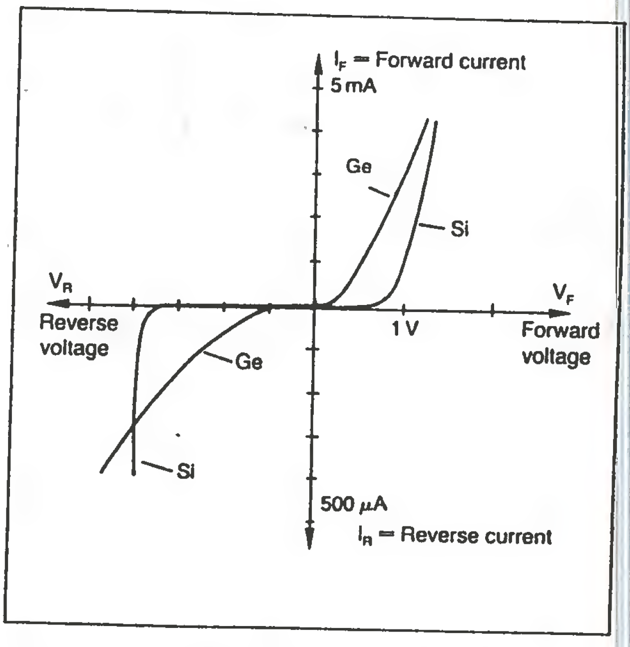


Fig. 3/3.6 a: Characteristic curves of Si and Ge diodes

3.6 Diodes/Zener diodes

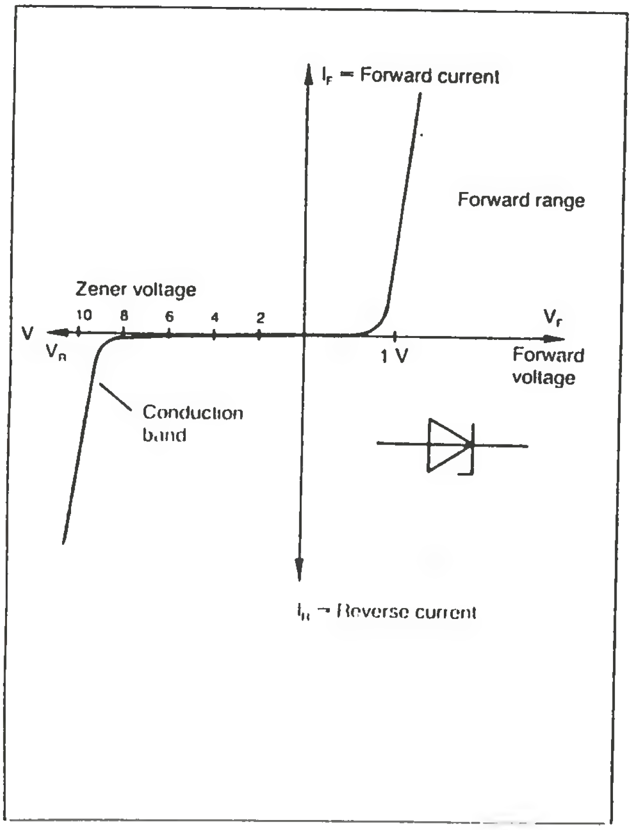


Fig. 3/3.6 b: Characteristic curve of the Zener diode

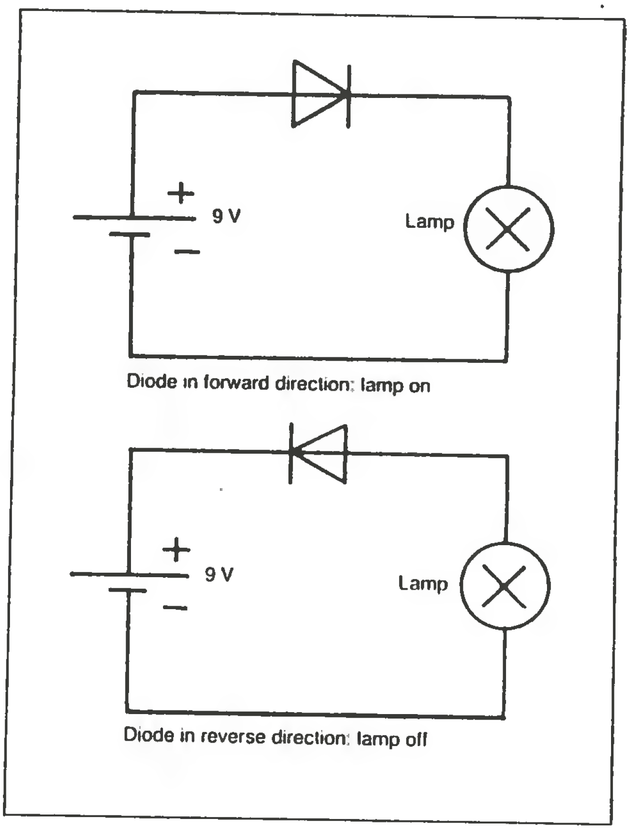


Fig. 3/3.6 c: Diode in forward and reverse direction

Checking diodes: thanks to their simple construction, diodes are easy to test. Disregarding certain specialist demands sometimes met in industry, only two faults can occur: short circuit and open circuit. These faults can be diagnosed with an ohmmeter which, according to the polarity, indicates conduction (low resistance) or open circuit (high resistance). The ohmmeter is used on ranges × 1 Ω, × 10 Ω or × 100 Ω.

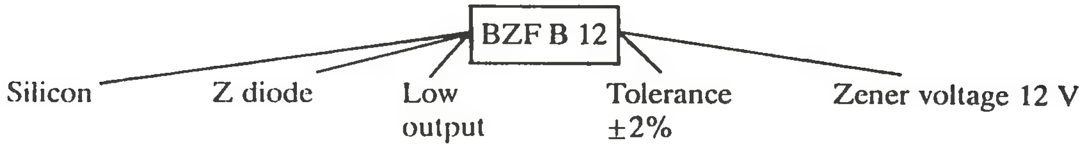
Zener diodes possess special characteristics. Unlike ordinary diodes, they are used in a reverse direction. From a certain voltage (the Zener voltage) the reverse current rises steeply. Zener diodes are used to stabilise voltage and can be supplied in about 50 Zener voltages from 2.4 to 500 V. The power dissipation ranges from 0.5 to 10 W. As the Zener voltage is dependent upon temperature, the temperature coefficient T_k is very important. For diodes with a Zener voltage of 5.6 V the T_k is near enough to zero. For Zener voltages > 5.6 V the T_k is negative, whilst for Zener voltages < 5.6 V it is positive.

Zener diodes are identified in a similar way to the other diodes. The reference number consists of letters which indicate the family, but the Z shows that it is a

Zener diode. ZF = low output to 0.5 W; ZD = output to 2 W; ZL, ZX = higher output to 10 W. The final digit of the reference number gives the Zener voltage, e.g. BZF12 = 12 V Zener voltage.

The tolerance indication is shown by the letter before the number which indicates the Zener voltage: A = ± 1%, B = ± 2%, C = ± 5%.

Example:



3/3.7

Bipolar transistors

The transistor was invented in 1948 by two American physicists. The name resulted from the combination of the two words "transfer" and "resistor". It is the most important component in electronics and it occurs both as an individual component and as the basic element of integrated circuits (ICs). A transistor has three connections (base, emitter, collector) and consists of two diodes wired in opposite directions. With the pnp transistor, the cathodes of the diodes constitute the input of the transistor, named "base". With the npn transistor, the base is the two anodes. The two diodes are called the base-emitter diode and the base-collector diode. Thus there are three semiconductor layers in a transistor. Transistors of the double diode type are called "bipolar".

So far as functioning is concerned, there is no difference between pnp and npn transistors. But the inverted polarities mean that the currents flow in the reverse direction.

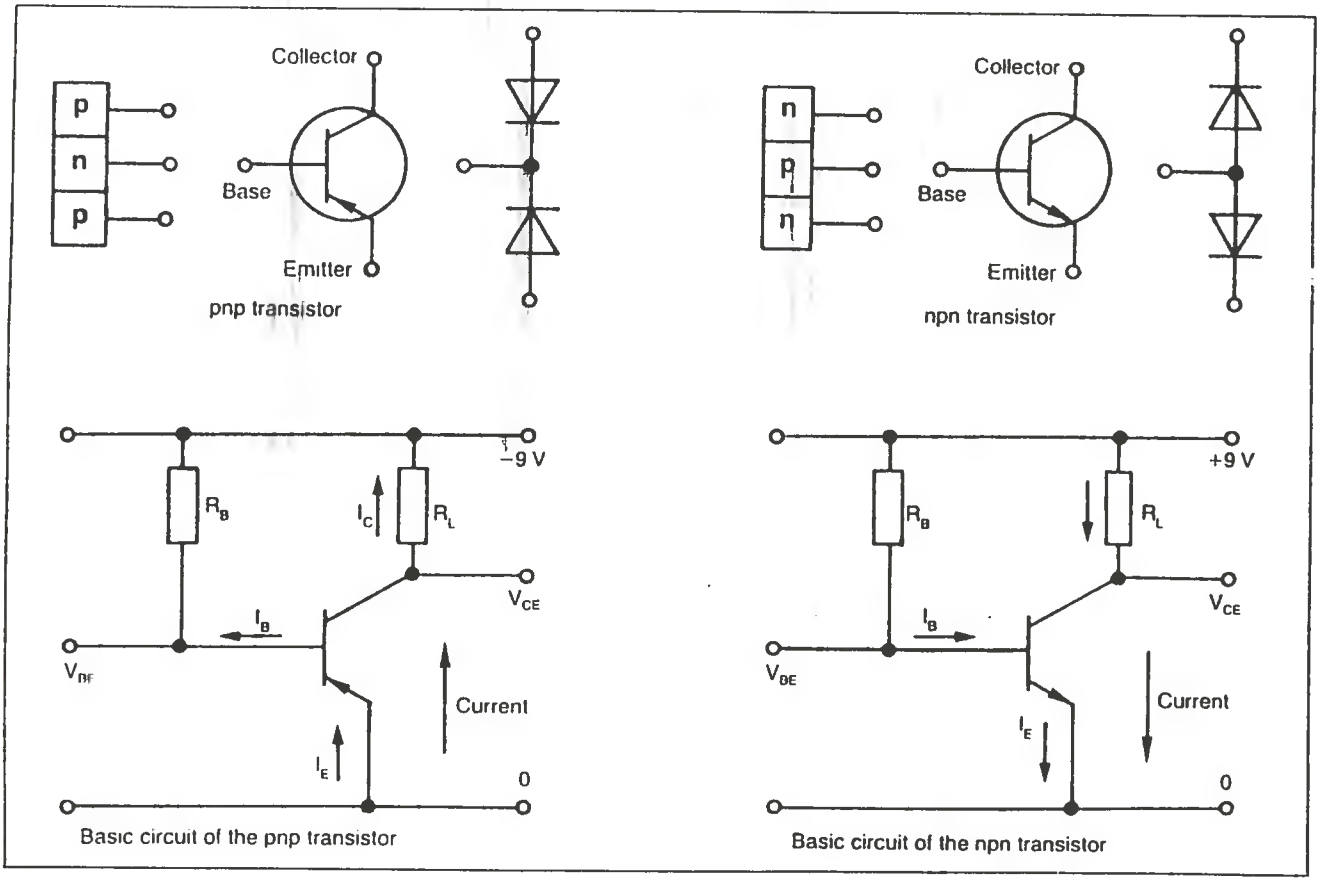


Fig. 3/3.7 a
pnp transistor

npn transistor

3.7 Bipolar transistors

$I_E = I_C + I_B$ (emitter current)

$\beta = \frac{I_C}{I_B}$ (current amplification)

$R_{BE} = \frac{V_{BE}}{I_B}$ (input resistance)

$R_{CE} = \frac{V_{CE}}{I_C}$ (internal resistance)

$P_{tot} = V_{CE} \cdot I_C$ (power dissipation)

The flow of current in the base emitter circuit begins when the base emitter voltage V_{BE} exceeds 0.65 to 0.70 V. The base current is of the order of 0.5 to 5% of the emitter current. This results in the collector current being from 95 to 99.5% of the emitter current. The principal characteristics of transistors are (see Chapter 6/3):

- I_C = collector current, indication of its maximum value, also named I_{CAV} (pulse operation).
- P_{tot} = total power dissipation, product of $V_{CE} \cdot I_C + (V_{BE} \cdot I_B)$ indicated in watts.
- V_{CBO}, V_{CEO} = dielectric breakdown voltage of diodes BC and BE in reverse direction. Stated in volts.
- B or β = current amplification factor, relationship between the collector current and the base current, dimensionless.
- f_T = transition frequency, frequency for which β is no longer in the region of 1.

Identification and types of transistors

The labelling of a standard transistor consists of two letters and three numbers. Transistors for special applications are identified by three letters and two numbers. The first letter indicates the material used: A = germanium; B = silicon. The second letter indicates the area of use, according to the table below. Abbreviations: LF = low frequency applications; HF = high frequency applications.

Table 3/3.7 a

C	= low power, for LF
D	= power, for LF
F	= low power, for HF
L	= power, for HF
P	= phototransistor
S	= switching transistor for low power
U	= switching transistor for high power

The type of transistor most widely used today is the junction transistor (planar transistor). It is particularly cheap to manufacture because a photolithographic process allows hundreds of transistors to be produced in a single operation on a silicon wafer. This process is possible for both low power and high power transistors. The so-called point transistor, in which the anode is in the form of a thin wire soldered on to a chip, is no longer used except in special high frequency applications.

3/3.8

The field effect transistor (FET)

With respect to the base material, field effect transistors are nothing more than transistors. With respect to their function, however, they are controllable resistors. In their mode of operation they resemble thermionic valves because, exactly as in the case of the valve, only one voltage (the gate voltage) is necessary for controlling the current. Unlike the bipolar transistor, no current flows in the control electrode (gate). This has the result that the input of the field effect transistor has very high impedance and does not load the control source.

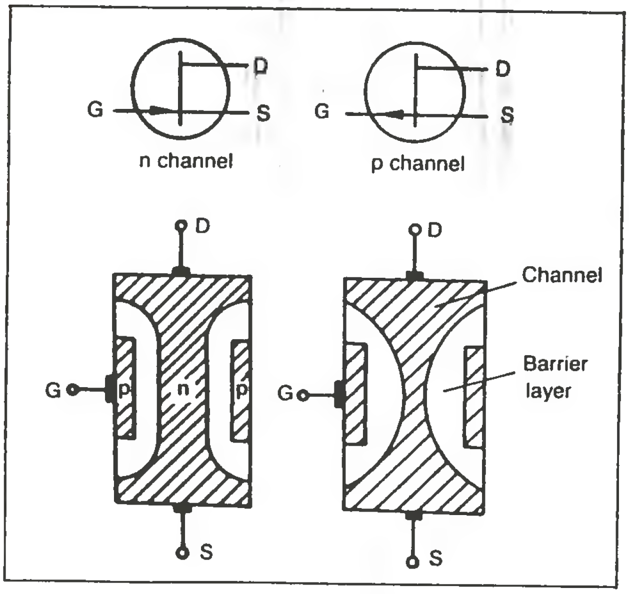


Fig. 3/3.8 a
FET barrier layer (principle)

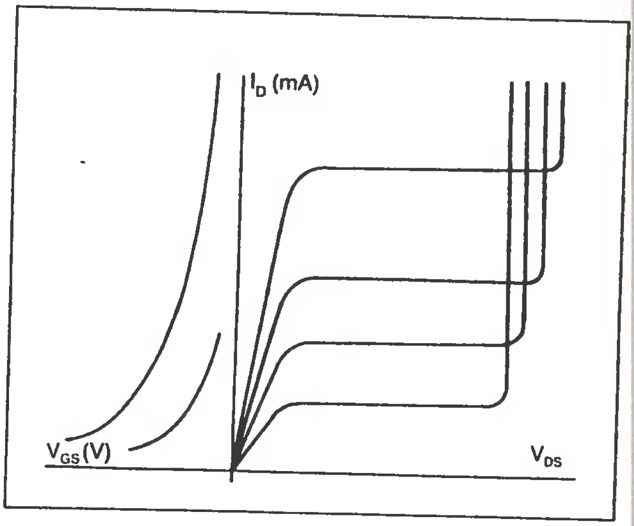


Fig. 3/3.8 b
Characteristic curves of a field effect transistor

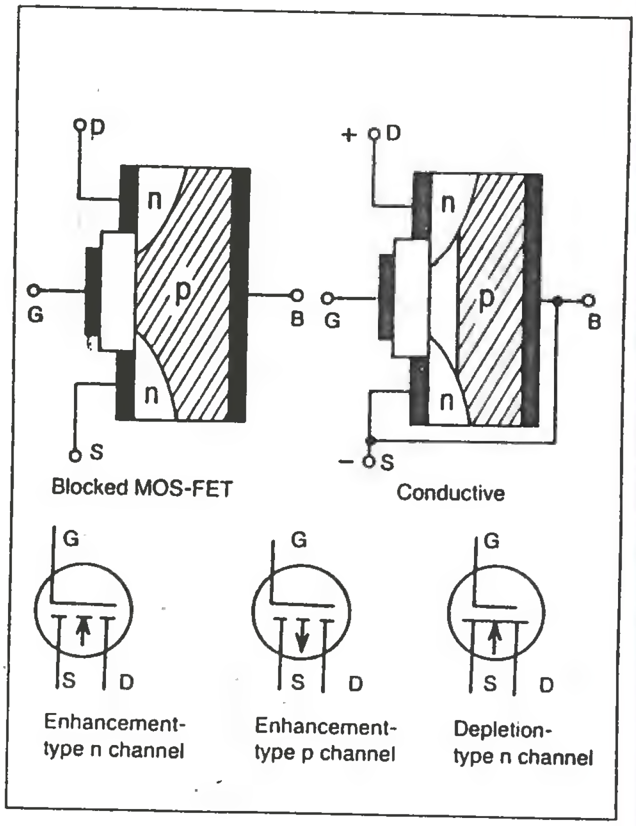


Fig. 3/3.8 c
MOS-FET (principle)

3.8 The field effect transistor

V_{DS} = drain source voltage
V_{GS} = gate source voltage
I_D = drain current
I_S = source current

Figure 3/3.8 a shows the graphical symbols and construction of an FET barrier layer. The name comes from the construction of the FET – between the two strongly doped gate connections there is a weakly doped "channel" which varies in thickness with the voltage applied (gate voltage). Between gate and "channel" a pn junction is formed with a barrier layer which operates as insulation. The left-hand diagram shows an open channel through which the electrons can flow. In the right-hand diagram the channel is contracted, preventing any flow of current. The two other electrodes – apart from the gate – are called "source" and "drain" in the field effect transistor. The current which is to be controlled flows between them.

Field effect transistors can be divided into two main groups:

- FET barrier layer (as described above).
- MOS-FET (metal oxide semiconductor).

With the MOS-FET (Fig. 3/3.8 c), the insulation between the gate and the channel is formed from a thin layer of silicon dioxide (SiO_2). The gate is a layer of aluminium deposited by vaporisation. The conductive channel forms between source and drain when a voltage is applied. This channel becomes broader or narrower according to the voltage applied. The substrate in which the channel forms constitutes the base for the electrodes, and is electrically connected to the source electrode. The MOS-FET family comprises the enrichment type and the depletion type. The enrichment type is self-blocking because, when the gate is open or when V_{GS} = 0 V, it is blocked. The depletion type behaves in the opposite way, and is conductive when the gate is open or V_{GS} = 0 V. The depletion type has the characteristic that I_D increases as much with positive as with negative gate voltage. It can therefore be controlled with voltages of both polarities. However, it is more usual to control it with a negative gate voltage.

3/3.10

The light dependent resistor (LDR)

The resistance of an LDR varies with the intensity of the light falling upon it. The resistance with strong light is just a few ohms (photo resistance) but with darkness it is 50 to 250 MΩ. The base material is cadmium sulphide or lead sulphide. An important characteristic is the spectral sensitivity which indicates how the resistance varies depending on the nature of the light which reaches it. LDRs are purely ohmic, and can therefore be used in direct and alternating current circuits. Apart from the usual LDRs which are sensitive to visible light, there are others which are sensitive to infrared or ultraviolet rays, with the result that effects can be produced from "invisible" light.

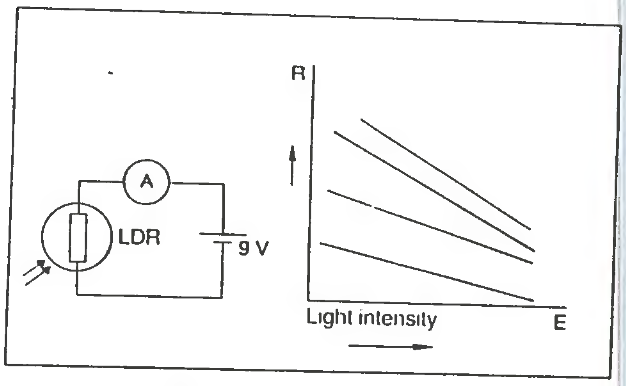


Fig. 3/3.10 a
Measurement circuit for LDRs

3/3.11

The photodiode

With photodiodes the pn semiconductor junction existing in all diodes is light sensitive. The photodiode is operated in the reverse direction. The reverse current increases when the junction is illuminated. In darkness a very small reverse current flows, which is called the dark current. The reverse current, also named the photo current, is proportional to the light intensity, with the result that the photodiode can be used directly for measuring light. The casings of photodiodes either are made of transparent glass or else have a small window with a small magnifying glass which allows the light to reach the photosensitive barrier layer. A particular advantage of the photodiode over the LDR is that with the photodiode the reverse current instantly changes with variations in intensity of the light. Whilst LDRs can be operated only at a frequency of a few hundred Hz, photodiodes can be used right up to the gigahertz range. The operating range varies from up to −30 V in the reverse direction to up to +0.2 V in the forward direction.

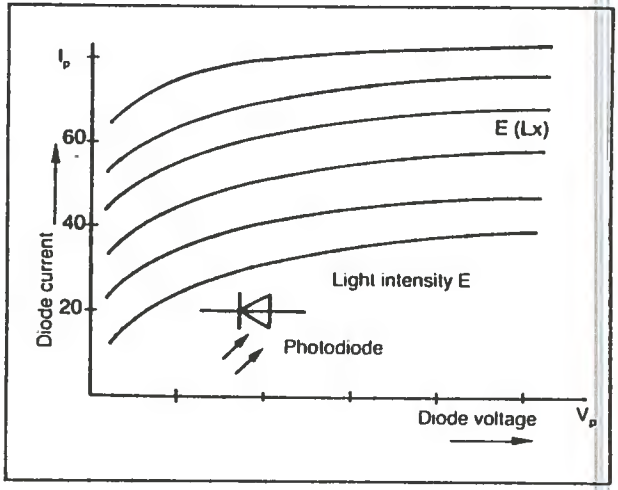


Fig. 3/3.11 a: Symbol of the photodiode
Diode current as a function of diode voltage for different light intensities E

I_D = diode current
V_D = diode voltage
E = light intensity

3/3.11

The photodiode

With photodiodes the pn semiconductor junction existing in all diodes is light sensitive. The photodiode is operated in the reverse direction. The reverse current increases when the junction is illuminated. In darkness a very small reverse current flows, which is called the dark current. The reverse current, also named the photo current, is proportional to the light intensity, with the result that the photodiode can be used directly for measuring light. The casings of photodiodes either are made of transparent glass or else have a small window with a small magnifying glass which allows the light to reach the photosensitive barrier layer. A particular advantage of the photodiode over the LDR is that with the photodiode the reverse current instantly changes with variations in intensity of the light. Whilst LDRs can be operated only at a frequency of a few hundred Hz. photodiodes can be used right up to the gigahertz range. The operating range varies from up to −30 V in the reverse direction to up to +0.2 V in the forward direction.

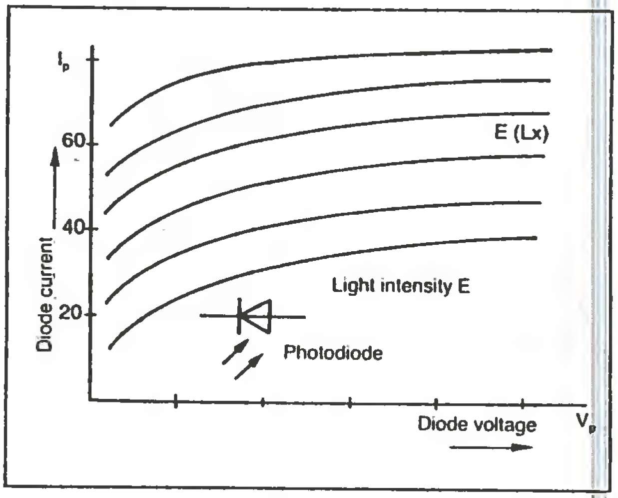


Fig. 3/3.11 a: Symbol of the photodiode
Diode current as a function of diode voltage for different light intensities E

I_D = diode current
V_D = diode voltage
E = light intensity

3/3.13

The thyristor

The thyristor is one of the principal components in the area of power electronics, where switching of large currents and voltages is involved. Its construction corresponds to that of a semiconductor diode with four layers. The sequence of the layers is pnpn. From the functioning point of view, three successive layers form a transistor, with the result that one can define an npn transistor and a pnp transistor, which are connected by bases and the collector. Thyristors can only block and conduct the current. They are made conductive by a so-called trigger pulse which allows a base current to flow; this starts up the thyristor and makes it conductive. The trigger pulse can be very short, just long enough for one of the two transistor sections to become conductive. Pulses of the order of microseconds are sufficient. Exactly as with a normal diode, a thyristor has a forward direction and a backward direction. The difference is that with a forward voltage no current flows until a trigger pulse has been applied to the control electrode. It is the base connection which constitutes the control electrode. Depending on type, thyristors are controlled by a positive or negative pulse. With most thyristors, it is the p layer which is used as the control electrode, and one refers to the cathode gate (G_c). If the control electrode is the n layer, one refers to the anode gate (G_a). The anode gate is triggered with a negative pulse. If the two control electrodes are accessible, the component becomes a thyristor tetrode. If only one control electrode is available, the component is a thyristor triode. Thyristor triodes cannot be switched off across the control electrode. Thyristor tetrodes can be triggered by one control electrode and be switched off by the other.

Principal characteristics of thyristors

- Peak inverse voltage (V_{DRM} or V_{RRM}): voltage peaks occurring with AC voltage which must not be exceeded.
- Forward voltage (V_T): between 1.4 and 2 V according to type.
- Power dissipation P_{tot}: product of forward voltage and effective limited current $P_{tot} = V_T \cdot T_{TRMS}$.
- Effective limited current (I_{TRMS}): median value of the current which must not be permanently exceeded.
- Current limiting value (I_{TSM}): maximum value of the short impulses of current ≤ 10 ms.
- Zero breakover voltage (V_{K0}): voltage with which a thyristor to which forward direction voltage is applied becomes conductive without a control pulse being applied to the ignition electrode (gate open). The zero breakover voltage should always be considerably greater than the operating voltage.

3.13 The thyristor

Thyristors are manufactured for currents ranging from some hundreds of milliamperes to several thousand amps. According to their power handling capacity, they are mounted in small plastic or metallic casings of different sizes, with thread connection for mounting on heat sinks.

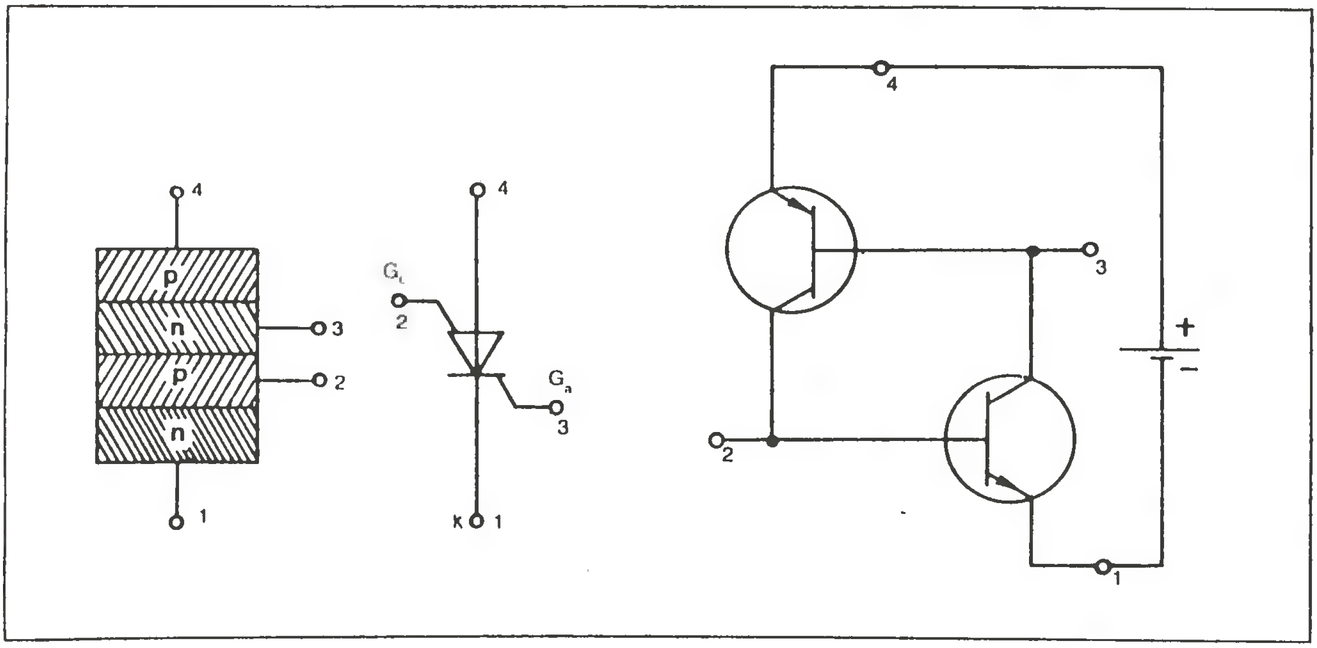


Fig. 3/3.13 a
Construction and circuit diagram for thyristors

Explanation of the characteristic curve: the curve shows the variations in the resistance of a thyristor. V_F is the voltage at which the thyristor becomes conductive. V_G and I_S are the bias and threshold current. When current drops below the threshold current, or when the extinction voltage is reached, which is a little lower than the bias, the transistor blocks once again. Because thyristors behave like normal diodes when conductive, they should be operated in series with a resistor.

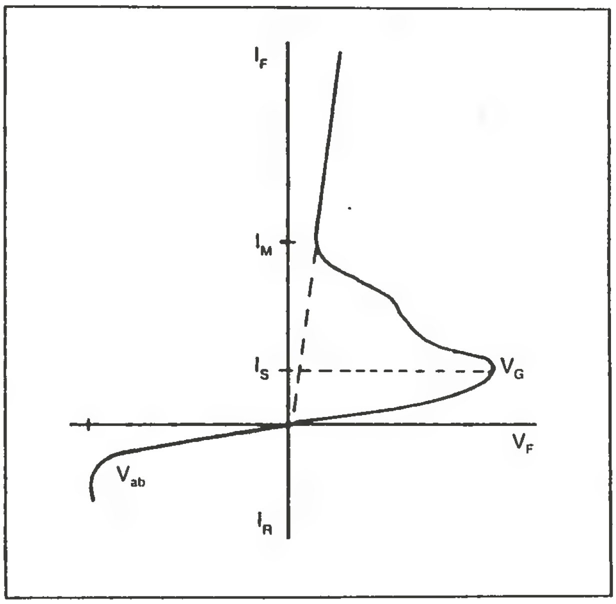


Fig. 3/3.13 b
Characteristic curves (resistance)

3/3.14

Triacs/diacs

A triac is produced by the head-to-tail wiring of two thyristors. It is therefore a thyristor which switches in two directions. The abbreviation comes from the description "triode alternating current switch". When it is supplied with alternating current, the triac is conductive in both directions according to the half wave. Triacs and diacs are similar components. Whilst the triac has a control electrode G, control of the diac is by means of the alternating voltage applied to it. When a certain value is exceeded, the diac becomes conductive. Diacs are often used as trigger diodes for thyristors and triacs where dimmer circuits, motors or temperature control circuits are involved. When using thyristors, triacs and diacs, noise suppression is a problem. At every firing, high frequency interference is produced in the thyristor. In order to prevent this noise modulating the mains voltage, all assemblies using thyristors and triacs should be noise suppressed.

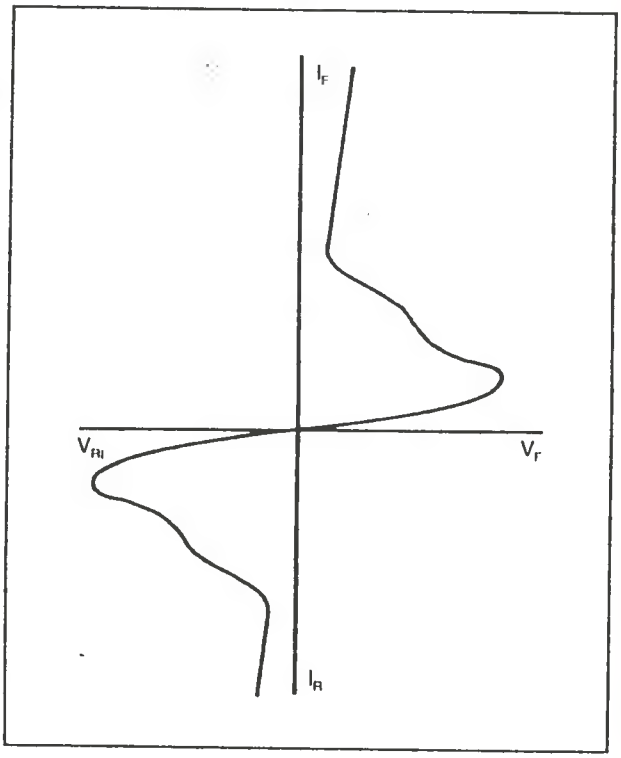


Fig. 3/3.14 c
Diac characteristic curve

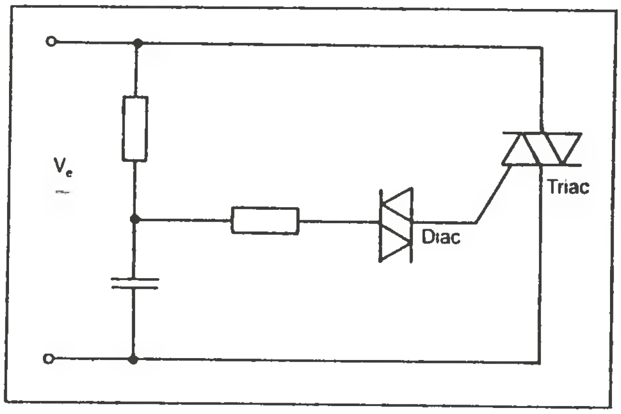


Fig. 3/3.14 d
Basic circuit diagram of a trigger circuit using a diac

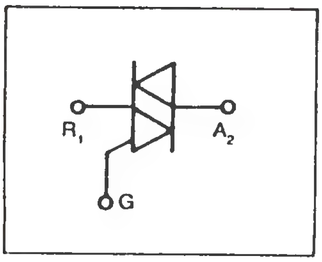


Fig. 3/3.14 a
Triac graphical symbol

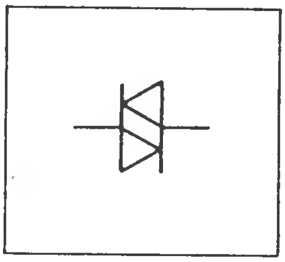


Fig. 3/3.14 b
Diac graphical symbol

3/3.15

The light emitting diode (LED)

Light emitting diodes are manufactured from gallium arsenide phosphide (GaAsP), gallium phosphide (GaP) or gallium arsenide (GaAs). They emit a red, green, yellow or blue light. Light emitting diodes are used in the forward direction, where they transform a part of the energy forming the current of the diode into light. The colour of the light depends upon the material used in the semiconductor. In a circuit, an LED behaves exactly the same as other diodes in both forward and reverse direction. In the forward direction, with a series resistance, it begins to emit light with a current from 0.5 to 1.5 mA. The forward voltage is from 1.5 to 3 V according to the type. The permissible reverse voltage is not very high. It must not exceed 2.5 to 5 V. A series resistance usually limits the current to the range 10 to 20 mA. LEDs serve as indicators and are used singly or grouped into segments or bands. Compared with filament lamps, they offer the advantages of a much longer life, smaller size, insensitivity to shocks and vibrations, and a rapid time response. LEDs have an instant response with alternating current. The identifying codes are similar to those of other diodes: the labelling is found on the cathode connector. A special form of LED is the IRED, an LED which emits infrared light and is particularly suitable for light barriers as it emits 50 times more strongly than a "normal" LED. To prevent overloading in the reverse direction, LEDs should always be used with a diode in parallel when connected to alternating current. In addition, it is necessary – as with direct current operation – to limit the current by means of a series resistance R_V. LEDs cannot simply be wired in parallel because the variation of the internal resistance, and thus the voltage drop, is too great. The only ways to overcome this are by very careful selection, or by using a very carefully measured series resistance for each individual diode. Series connection is not critical and can be effected across a joint series resistor. The principal characteristics of LEDs are:

- Forward current (I_E), adjustable by a series resistor R_V.
- Reverse voltage (V_R) which must not be exceeded (with alternating current the diode should be wired in parallel).
- Power dissipation (P_{tot}), indication in mW as shown in the data tables.
- Forward voltage (V_F) < 3 V.
- Light collecting surface (A), in mm² as shown in the data tables.
- Wavelength (λ) of the maximum intensity, indication in nm.

3.15 The light emitting diode

Colour	Material	Forward voltage
Infrared	Gallium arsenide (GaAs)	1.2 to 1.4 V
Red	Gallium arsenide phosphide (GaAsP)	1.4 to 1.8 V
Yellow	Gallium arsenide phosphide (GaAsP)	2.0 to 2.6 V
Green	Gallium arsenide phosphide (GaAsP)	2.2 to 2.8 V

Table 3/3.15 a: Colours of LEDs

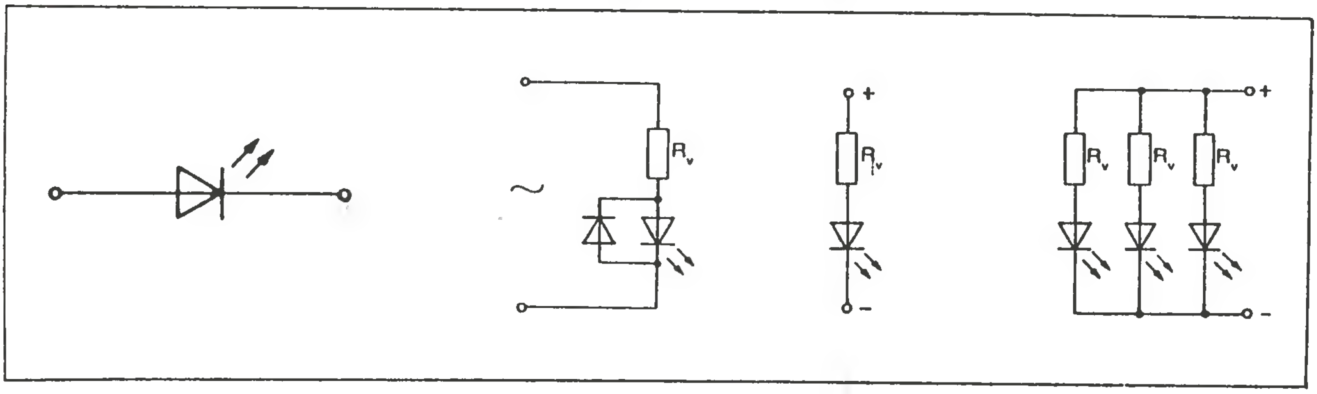


Fig. 3/3.15 a
Symbol of the LED

Protection circuit for LEDs in alternating current operation

Operation with series resistance R_V in direct current

Parallel switching of LED with R_V

3/3.16

The liquid crystal display (LCD)

Unlike light emitting diodes, liquid crystal displays do not emit any light. When switched on, they plane polarise incident light; when switched off, they do not plane polarise the light. The controlling voltages for LCDs lie between 1.5 and 50 V. As practically no current flows, LCDs can be controlled without power and connected directly to integrated MOS circuits. The advantages of this low power dissipation are, however, offset by disadvantages: where the ambient light is low, the display needs additional illumination; also, the range of operating temperatures of LCDs is somewhat limited, and the response time is poor. As the main advantage of low power dissipation outweighs the disadvantages in calculators, etc., LCDs are found in more and more applications. LCDs are offered as complete assemblies in which the number and type of segments can be chosen in such a way that either letters or numbers, or both, can be represented.

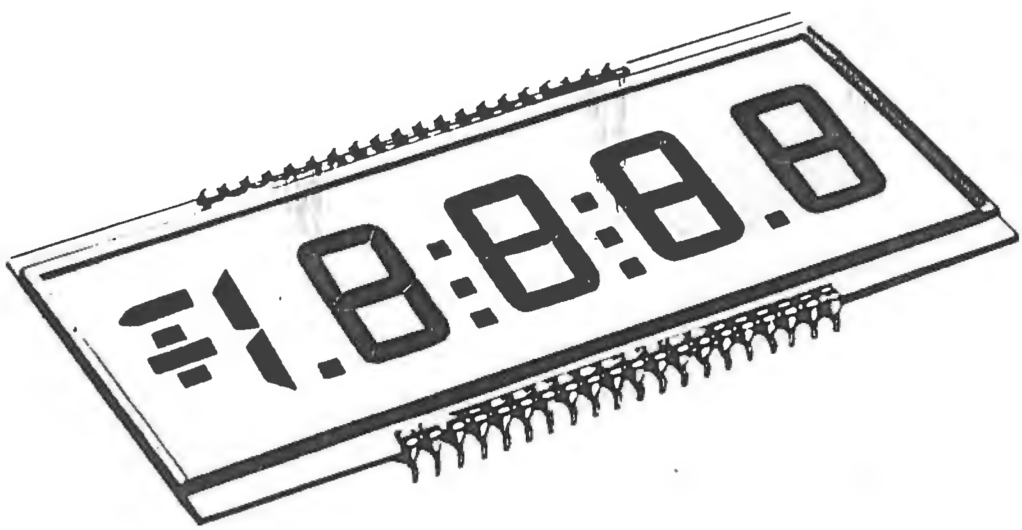


Fig. 3/3.16: Liquid crystal display in dual-in-line (DIL) casing

3/3.17

The Hall effect cell

A Hall effect cell is a magnetic field transducer which generates a voltage proportional to the intensity of any magnetic field applied perpendicularly to its output terminals.

Consider a conductive or semi-conductive metallic plate carrying a current along its x-axis; this current can be considered to be the result of the movement of positive and negative charges travelling at a velocity v in opposite directions along the x-axis, their movement being caused by placing the plate in a magnetic field of strength B which is directed along the z-axis. The positive particles are deflected towards the right and accumulate at the right-hand edge of the plate, and the negative charges are deflected in the other direction, collecting at the opposite edge of the plate. The result of this is an electric field E, directed towards the positive y-axis. This field causes a potential difference across the plate of the order of one microvolt.

Fig. 3/3.17 shows the circuit diagram and operating principle of a Hall cell. I_1 is the value of the current, B the strength of the magnetic field, a the width of the cell and K the "Hall constant".

The voltage obtained at the terminals of V_2 is given by:

$$\boxed{V_2 = K \cdot I_1 \cdot \frac{B}{a}}$$

From Ohm's Law, $V_1 = I_1 \cdot R$, where R is the resistance. Therefore:

$$\boxed{V_2 = K \cdot V_1 \cdot \frac{B}{R \cdot a}}$$

and as K, R and a are constants:

$$\boxed{V_2 = \alpha \cdot V_1 \cdot B}$$

There are many possible applications:

1. The cell is a device which can be used as an electronic multiplier. Since $V_2 = \alpha \cdot V_1 \cdot B$, V_1 and B can represent the multiplication factors, and with α a known constant, V_2 can be measured and the product of V_1 and B deduced. This application is used in certain analogue calculators.

2. If V_1 and B are proportional to the voltage and the magnetic intensity in a circuit, the Hall cell can be used as a wattmeter. If it is placed in an electro-magnetic field in such a way that E is aligned along the length L and the field B is at right angles to the cell, the voltage is numerically equal to the product of $E \cdot B$; this is known as a Poynting vector, and represents the power in the circuit.

3. The same formula gives:

$$\boxed{B = \left(\frac{a}{K_1}\right) \cdot V_2}$$

which shows that V_2 is proportional to B. The cell can thus be used to measure the magnetic field, or, better, its distribution

in a particular place, for example in the gap of a magnet.

4. For measuring large direct currents, a loop (or even a part of a turn) can be used; if this carries the current it can be considered to constitute the primary of a transformer in which there is a gap. The magnetic induction in this gap is proportional to the direct current and this can be measured with a Hall cell.

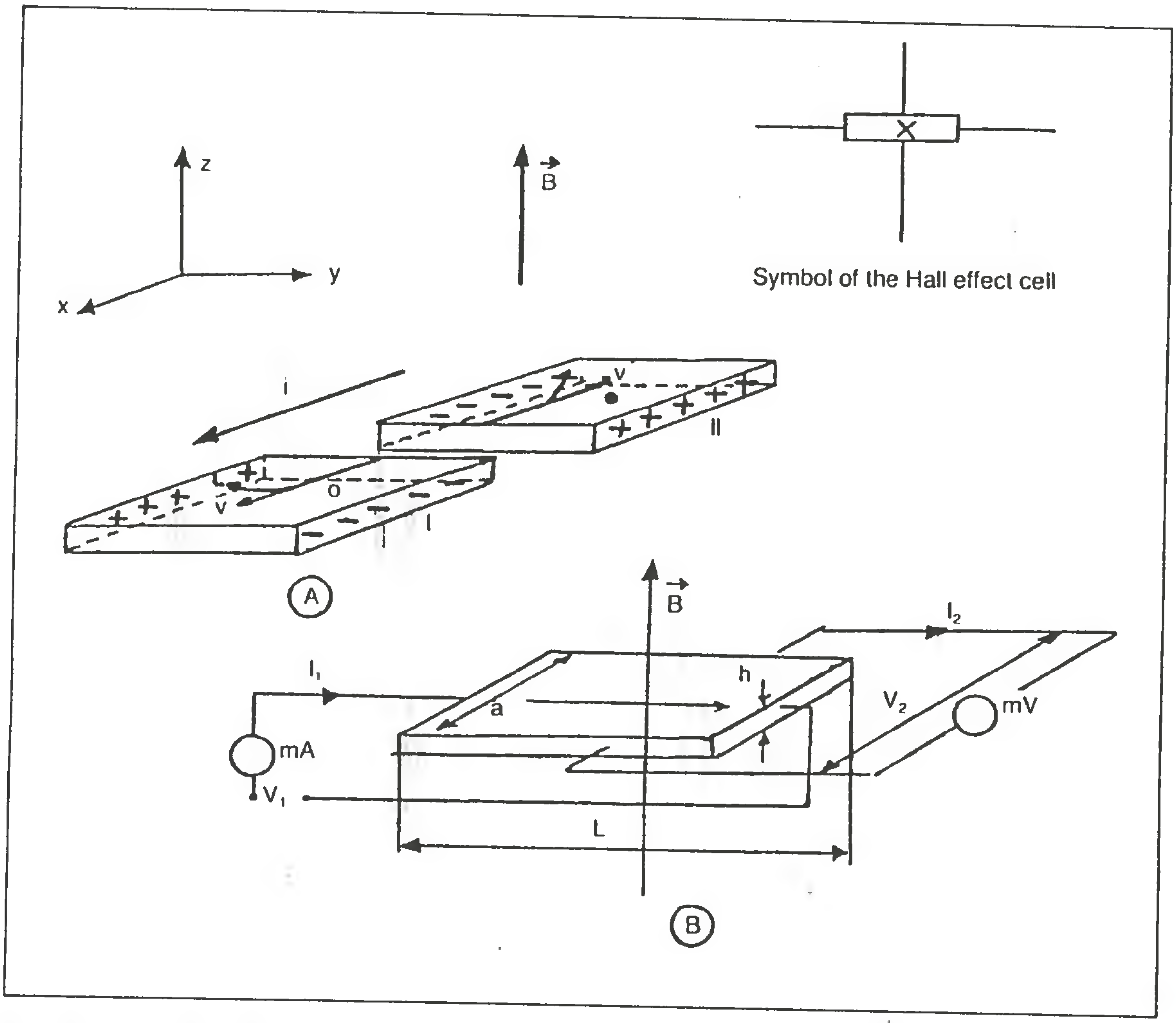


Fig. 3/3.17: Hall effect cell
A Principle
B Use

3/3.20

Transformers

Transformers are converters of alternating voltage. They consist of at least two coils and a magnetic core which must be common to both coils (Fig. 3/3.20a).

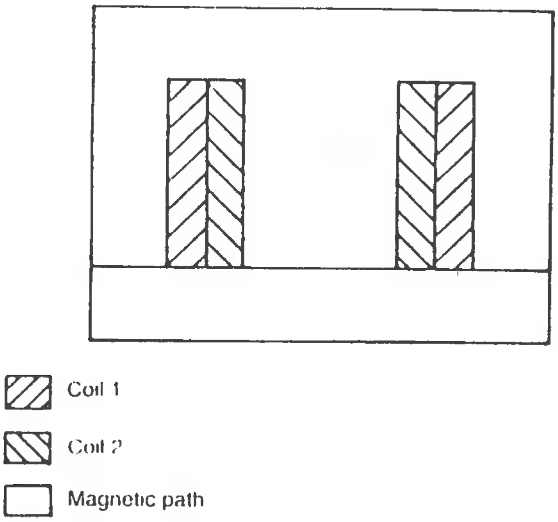


Fig. 3/3.20 a: Diagram of a simple transformer in cross-section

The application of an alternating voltage V_1 to the terminals of coil 1 generates an alternating voltage V_2 at the terminals of coil 2 because of the magnetic linkage.

The voltage and current supplied by coil 2 depend on:

- V_1: the supply voltage of the primary of the transformer.
- The number of turns of each of the coils.
- The cross-section of the wire used to manufacture coils 1 and 2.
- The magnetic material (cross-section, material) used for the core.

Transformers form an integral part of most power supply units. When used in conjunction with a rectifying circuit they commonly provide the DC voltage necessary for electronic equipment.

Transformers are also used in another area, that of impedance matching. A transformer can also be viewed as an impedance converter: in this form it is commonly found in audio equipment.

Transformers used in amateur electronics may range in power from 0.2 VA to about 500 VA. This power rating is the maximum power that the transformer can handle without overheating, and it forms an important part of the specification of the transformer.

The size (and price) of a transformer is proportional to its power rating.

For a single primary (a single coil 1) there can be several secondaries (coils 2 and 3, etc.) which supply several different voltages; this is particularly useful when constructing a piece of equipment requiring a multi-voltage supply.

Most general purpose mains transformers have a choice of input and output voltages known as "tappings", because they are tapped into the primary winding at different points so that the total length of the primary coil can be varied. The primary voltage can generally be

adjusted for a range of mains voltages such as may be found in other countries, for example 110 V, 130 V, 210 V, 230 V and 250 V.

Building a DIY mains supply transformer

1st stage

Determining the necessary power rating or nominal wattage of the transformer. This is calculated by adding up all the wattages used by the equipment with which the transformer is to be used.

This calculated wattage must be increased because, depending on the rectifying technique used, there will be portions of the voltage, and thus the available power, which are consumed by the rectifier. This means that a correction factor, shown in Table 1, must be applied to the calculated wattage to obtain the nominal wattage.

2nd stage

Determining the cross-section of the magnetic core. This cross-section depends on the nominal wattage of the transformer. Table 2 shows the data necessary for this calculation.

The casing of the coils can be made from synthetic material or cardboard.

The output terminals of the coils must be grouped together on the side of the coil support and identified by a colour or some other means. Insulating paper must be inserted between each coil to prevent the coils from contacting each other.

When buying a commercially available transformer it is worth checking to see that the manufacturer has used a shellac resin to insulate the wires of the coils. This process requires baking the transformer, and, as this cannot easily be carried out at home, sheets of insulating paper are generally sufficient for low wattages.

However, it is necessary to pay extra attention to the enamelled copper wire, checking:

- that the enamel is not scratched,
- that the turns are wound continuously and do not cross one another.

Whilst doing this, avoid repeatedly unwinding and rewinding the same wire (more than once or twice) because the lacquer is brittle and will flake off.

The magnetic core comprises specially treated parallel sheets which limit the eddy currents which would otherwise cause losses of energy in the transformer. Such losses are known as core losses.

Table 1

Circuit	Channel 1	With centre tap	With bridge rectifier	With two secondary windings
Rectification factor	2.25	2	1.6	1.6

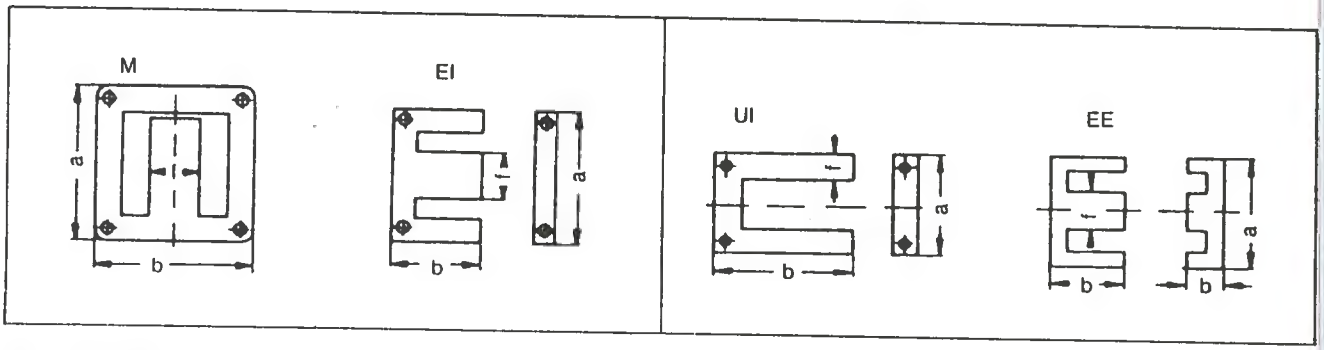


Fig. 3/3.20 b: Layout of the magnetic core

Several kinds of magnetic core exist. These include:

- The metal clad (Fig. 3/3.20b).
- The toroid, which is circular, and therefore has a lower external magnetic field than the other types. This has very important applications with power supplies used with equipment sensitive to mains related interference.

When assembling the magnetic core, it is important to clamp the sheets tightly together, as otherwise they will vibrate during operation, causing a hum and risking damage to the coil inside (short-circuit). A tight fit is ensured by using four bolts.

Calculations and formulae connected with transformers

The power of the secondary is the sum of all the wattages used downstream of the transformer.

$$\boxed{P_{secT} = P_{sec1} + P_{sec2} + \ldots + P_{secN}}$$

Secondary nominal wattage:

$$\boxed{P_{sec} = V_2 I_2 \text{ [W]}}$$

Secondary wattage:

$$\boxed{P_{sec} = V_1 \cdot K_f \text{ [W]}}$$

where K_f is the coupling factor.

Formula connecting the primary wattage to the secondary wattage:

As with nearly all electrical and electronic equipment, the transformer has its own internal losses:

- Resistance losses: power which is dissipated in the form of heat due to the resistance of the coils.
- Core losses: losses in the magnetic circuit.

Because of this, it is usual for the secondary wattage to be less than the primary wattage. The ratio of the two wattages, η, is defined by:

$$\boxed{\eta = \frac{P_2}{P_1}}$$

where P_2 and P_1 are the secondary and primary power ratings respectively.

Another essential formula for transformers is the one connecting the

voltages to the number of windings of the coils:

$$\frac{N_1}{N_2} = \frac{V_1}{V_2}$$

This formula is theoretically accurate, but in reality the various losses render it imprecise.

Table 2 shows the number of turns to wind as a function of the voltage and the magnetic circuit. This number has been determined from the secondary wattage, increased by the rectifying factor linked to the type of rectification used. The same table gives the current density for the inner and outer coils. This density allows the calculation of:

- The cross-section of the enamelled wire:

$$S_1 = \frac{I_1}{D_1}\,[\mathrm{mm}^2]$$

where S_1 is the cross-section of the primary
D_1 is the primary density

- The diameter of the primary coil, ϕ (mm):

$$\phi_1 = \sqrt{\frac{S \times 4}{\pi}}\,[\mathrm{mm}]$$

- The number of turns in the primary winding (N_1/V being given in Table 2):

$$N_{prim} = \frac{N_1}{V} \cdot V_{prim}$$

- The number of turns in the secondary winding (N_2/V being given in Table 2):

$$N_{sec} = \frac{N_2}{V} \cdot V_{sec} \times Fr$$

where Fr is the rectification factor (see Table 1).

- The cross-section of the wire of the secondary winding:

$$S_2 = \frac{I_2 \cdot Fr}{D_2}\,[\mathrm{mm}^2]$$

- The diameter of the secondary winding:

$$\phi = \sqrt{\frac{S_2 \times 4}{\pi}}\,[\mathrm{mm}]$$

Example of calculation (using factors determined from Table 2)

Task: to construct a power supply transformer, the characteristics of which are:

220 V/1 A for the primary
24 V/1 A for the secondary on one tapping
30 V/5 A for the secondary on a second tapping

A bridge rectifier will be used:

$P_{sec1} = V_{sec1} \times I_{sec1} \times Fr = 24 \times 1 \times 1.6 = 38.4$ W

$P_{sec2} = V_{sec2} \times I_{sec2} = 30 \times 5 = 150$ W

$P_{secT} = P_{sec1} + P_{sec2} = 38.4 + 150 = 188.4$ W

The magnetic path factor can be determined from Table 2. In this case it needs to be 130a, because a wattage must be chosen which is greater than the minimum required, which in this case is 188.4 watts. This gives for the transformer an efficiency rating of around 0.9.

3.20 Transformers

Table 2: Table of values given in standard DIN 41 302

Power														
1 input and 1 or 2 outputs (W)		VA	4	12	25	50	70	95	120	175	250	320	370	450	550
Extra windings (W)		VA	3	9	21	40	65	75	100	155	230	290	340	410	510
Magnetic path references			M 42v	M 55	M 65	M 74	M 85a	M 85b	M 102a	M 102b	EI 130a	EI 130b	EI 150a	EI 150b	EI 150c
Efficiency factor			0.6	0.7	0.77	0.83	0.84	0.86	0.88	0.89	0.9	0.91	0.92	0.93	0.94
Primary – turns per volt		N_1	23.4	11.4	7.8	5.68	4.51	3.2	3.5	2.34	3.3	2.59	2.59	2.08	1.74
Secondary – turns per volt		N_2	34.8	14.1	9	6.3	4.95	3.5	3.86	2.46	3.51	2.72	2.72	2.18	1.8
Density	inside	$\frac{A}{mm^2}$	4.5	3.8	3.3	3	2.9	2.6	2.4	2.3	1.7	1.7	1.5	1.5	1.5
	outside	$\frac{A}{mm^2}$	5.2	4.3	3.6	3.4	3.3	3	2.8	2.7	2.2	2.1	1.9	1.9	1.8

$P_{prim} = P_{sec}/\eta = 188.4/0.9 = 209.33$ W

$N_{prim} = N_1/V \times V_{prim} = 3.3 \times 220 = 726$ turns

$N_1/V = 3.3$ (from Table 2 for a transformer of 250 watts)

$I_{prim} = P_{prim}/V_{prim} = 209.33/220 = 0.9515$ A approx. $= 1$ A

$S_{prim} = I_{prim}/D_1 = 0.9515/1.7 = 0.559\ mm^2$

$\phi_1 = \sqrt{\frac{S_{prim} \times 4}{\pi}} - 0.843$ approx. $= 0.85$ or 0.9 depending upon the supplier

$N_{sec1} = N_2/V \times V_{sec1} \times Fr = 3.51 \times 24 \times 1.6 = 134.78 = 135$ turns (Fr from Table 1)

$N_{sec2} = N_2/V \times V_{sec2} = 3.51 \times 30 = 105.3 = 105$ turns

$I_{sec1} = 1$ A

$S_{sec1} = I_{sec}/d_2 = 1/2.2 = 0.45$

$\phi_{sec1} = \sqrt{\frac{0.45 \times 4}{\pi}} = \sqrt{0.57} = 0.754 = 0.8$ mm

$S_{sec2} = I_{sec2}/d_2 = 5/2.2 = 2.27$

$\phi_{sec2} = \sqrt{\frac{S_{sec2} \times 4}{\pi}} = \sqrt{\frac{2.27 \times 4}{\pi}} = \sqrt{3.03} = 1.74 = 1.8$ mm

3/3.21

Accumulators/ batteries

Batteries and accumulators are portable power supplies; they are generally divided into two separate categories, so-called dry batteries and the older but still used liquid-filled types. Dry batteries generally supply current by a chemical phenomenon using solid matter such as zinc or carbon, for example. A typical dry battery is composed of a zinc body and a carbon electrode, the two being connected by an electrolyte which allows a chemical exchange. The electrolyte is a paste with an ammonium chloride base. Such batteries can frequently be found in domestic appliances, and the individual cells, which produce 1.5 V each, can be placed in series to give a supply voltage commonly of 6 V or 9 V.

The second category includes lead-acid accumulators. These need to be "charged" with a high current before use, and they can be recharged many times during their lifetime. They are universally used in cars, where they allow a high current to be drawn to start the engine, and they are thereafter recharged by the running engine through a generator or alternator. The electrodes of lead-acid batteries are both made of pure lead, and the electrolyte is sulphuric acid.

Nickel-cadmium accumulators are also used in certain applications, as they are much lighter than lead-acid accumulators, but they suffer from many other drawbacks and are relatively expensive to construct. They are sometimes used as back-up power supplies in computer systems and radios.

1st category		
Type	Voltage per cell	Application
Zinc carbon dry battery	1.5 V	Universal, radio
Alkali manganese	1.5 V	For use with high loads and down to −20°C
Mercury oxide	1.35 V	Nominal voltage remaining constant for a long time Watches, etc. Battery can be very small
2nd category		
Type	Voltage per cell	Application
Lead	1.8 V to 2 V	Cars, high load
Nickel-cadmium	1.25 V	Universal use: equivalent to dry batteries, plus portable equipment

Nickel-cadmium dry batteries (NiCad)

These are rechargeable batteries which have been developed for electrical and electronic equipment which needs to be portable. The charging time of these cells is between 14 and 16 hours. This time can be reduced to one or two hours for quick charging types.

NiCad batteries can safely be charged continuously: this is the reason why they are often used as back-up supplies in low

power applications such as the battery-backed CMOS RAM in the BBC Master computer.

To charge these batteries, the charging current must be constant, the voltage from it being of necessity slightly higher than the nominal voltage of the cell. The manufacturer's specification as to charge rate is given on each cell and must be adhered to.

Warning: If nickel cadmium batteries overheat, they can catch fire or explode!

They should not be opened as the contents are toxic.

An accumulator should never be short-circuited as it will deteriorate very quickly. It should never be connected the wrong way round, whether on charge or on discharge. It is very difficult to use accumulators in parallel without creating a circulating current between them, because two identical cells are not usually available, and any slight differences in their state of charge will also cause the same problem. It is better to use a single accumulator of higher power.

3/3.23

Quartz crystals

Quartz crystal oscillators are made from crystals of silicon dioxide (SiO_2) which are both found naturally and manufactured artificially in the laboratory. In electronics, their piezo-electric properties are used to stabilise oscillating circuits.

The electrical and mechanical operation of a quartz crystal is based on the "piezo-electric" effect discovered by the Curies in 1880.

If a quartz crystal is subjected to an electric voltage, it flexes or bends. If the same crystal is squeezed mechanically, a small electrical voltage is produced across the crystal. This effect is called the piezo-electric effect and is used in crystal pick-ups for record players. Quartz is a good material for this because it takes a relatively long time to relax to its original state once disturbed. This means it can be set "ringing" if the frequency of the incoming alternating current is resonant with the crystal's natural relaxation frequency. As the crystal relaxes, the voltage produced is reversed and a graph, typical of an RLC oscillator, is produced (Figs. 3/3.23 d and e).

The resonant frequency of the quartz crystal is linked to its geometry and there are four main types, each with its characteristic oscillation frequencies.

Geometry and type of oscillation

Bending or flexing oscillation (bar or tuning fork shape)	5 . . . 100 kHz
Longitudinal oscillation (bar or tuning fork shape)	60 . . . 200 kHz
Surface oscillation (lozenge shape)	150 . . . 1000 kHz
Bulk oscillation (various shapes)	50 kHz . . . 200 MHz

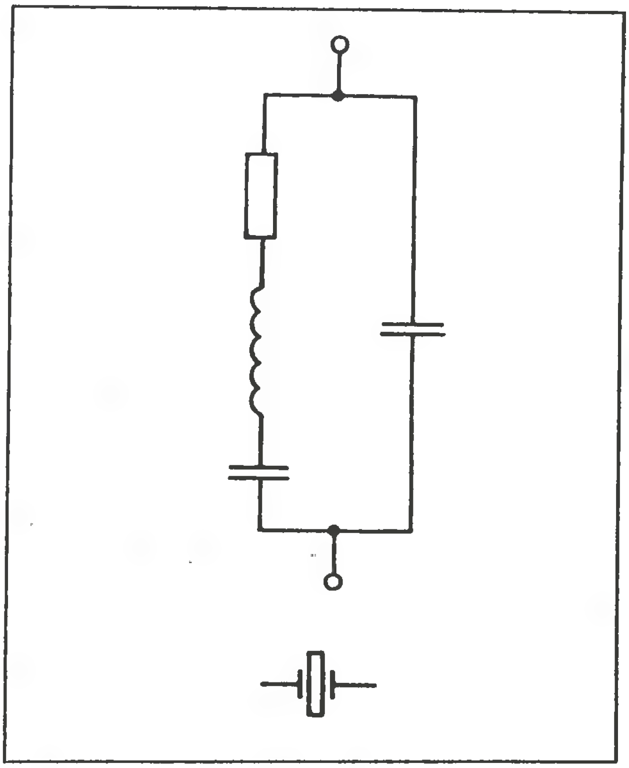


Fig. 3/3.23 a: Symbol and equivalent electrical diagram of a quartz crystal

Construction and operation of a tuning fork type low-frequency quartz crystal

"Low-frequency" tuning fork quartz crystals are mostly manufactured from synthetic quartz. The resonant frequency of the crystal is determined principally by its dimensions. The tuning fork is carved from a wafer of quartz which is ground in a particular orientation of the crystal. By positioning metal electrodes, the tuning fork quartz can be made to oscillate. The electrodes are so positioned at the ends of the forks as to produce movements of the flexural type. When a voltage is applied to the electrodes, the outer edge of each strip expands whilst the inner edge contracts, producing a movement of the strips towards each other. When the polarity is reversed, the inner edge expands, the outer edge contracts and the strips move away from each other. The movement of the strips is produced with a minimum of energy at the resonant frequency of the crystal (Fig. 3/3.23 b).

Electrical properties

The quartz crystal is a component and its equivalent electrical circuit is shown in Fig. 3/3.23 c. The parameters L1, C1 and R1 are in ratio with the piezo-electric properties of the crystal. C_0 is the parallel capacity between the electrodes and represents the sum of the electrode-to-quartz capacities, plus that of the casing.

A better understanding of the characteristics of the quartz crystal can be obtained by carrying out a transmission test to determine its real impedance. In this transmission test the quartz crystal behaves like a narrow band-pass filter which has a maximum transmission at the resonant frequency and a minimum at the non-resonant frequencies.

The maximum transmission is found at the resonant frequency when XL1 = XC1. This frequency defines the series resonant frequency by means of the parameters L1 and C1. These parameters are the most easily measured.

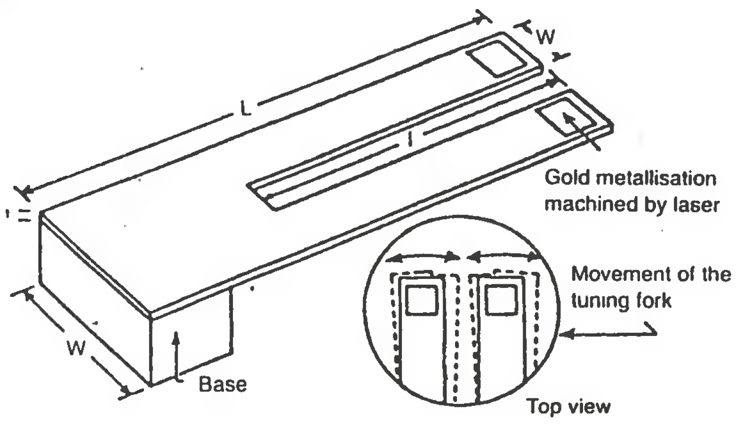


Fig. 3/3.23 b: Mechanical parameters of the tuning fork

Equation (1) defines the series resonant frequency f_s.

$$f_s \cong \frac{1}{2\pi\sqrt{L1 \cdot C1}} \qquad \ldots(1)$$

Equation (2) defines the non-resonant frequency f_a.

$$f_a \cong \frac{1}{2\pi\sqrt{\frac{L1 \cdot C1 \cdot C_o}{C1 + C_o}}}$$

$$\cong f_s \left\{1 + \frac{C1}{2C_o}\right\} \qquad \ldots(2)$$

As the quartz crystal is a tuned circuit comprising a large inductance and a small capacitance, it is interesting to examine the reactance of the circuit as a function of the frequency. The equivalent circuit of Fig. 3/3.23a can be reduced to a reactance X_e, in series with a resistance R_e, as shown in Fig. 3/3.23c. In the frequency range below f_s, X_e is capacitive.

At f_s, X_e is equal to 0, and above f_s, X_e is inductive as shown in Fig. 3/3.23d.

Oscillators which function at (or below) f_s are called series resonance oscillators or oscillators with negative reactance.

Those which function above f_s are called oscillators with positive reactance or parallel oscillators.

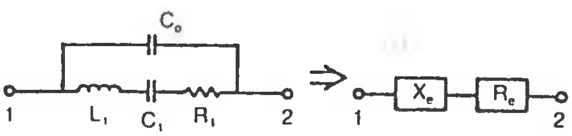


Fig. 3/3.23 c: Equivalent circuits

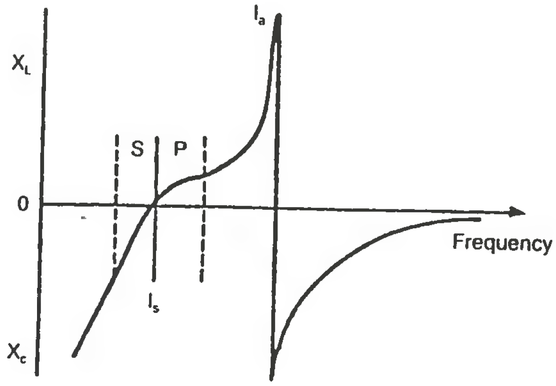


Fig. 3/3.23 d: Variation in the reactance as a function of the frequency

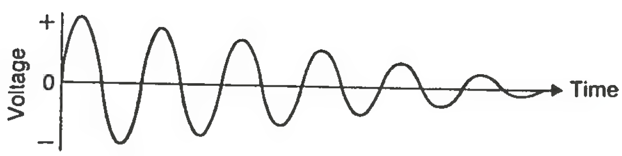


Fig. 3/3.23 e: Constant frequency as the amplitude tends to zero

Specifications and parameters of quartz oscillators

Ageing

This is the long-term frequency stability of a quartz crystal when it functions at a constant temperature. Any shift in frequency with time is expressed in parts per million (ppm) for a specified length of time, and is generally a logarithmic function. The longer the operating time given, the smaller the shift.

3.23 Quartz crystals

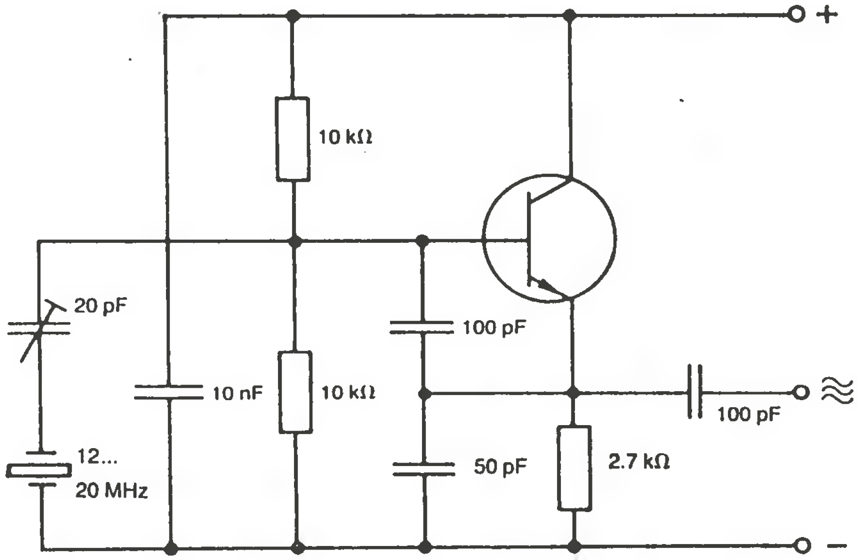


Fig. 3/3.23 f: Colpitts-type quartz oscillator: quartz crystal in the base circuit

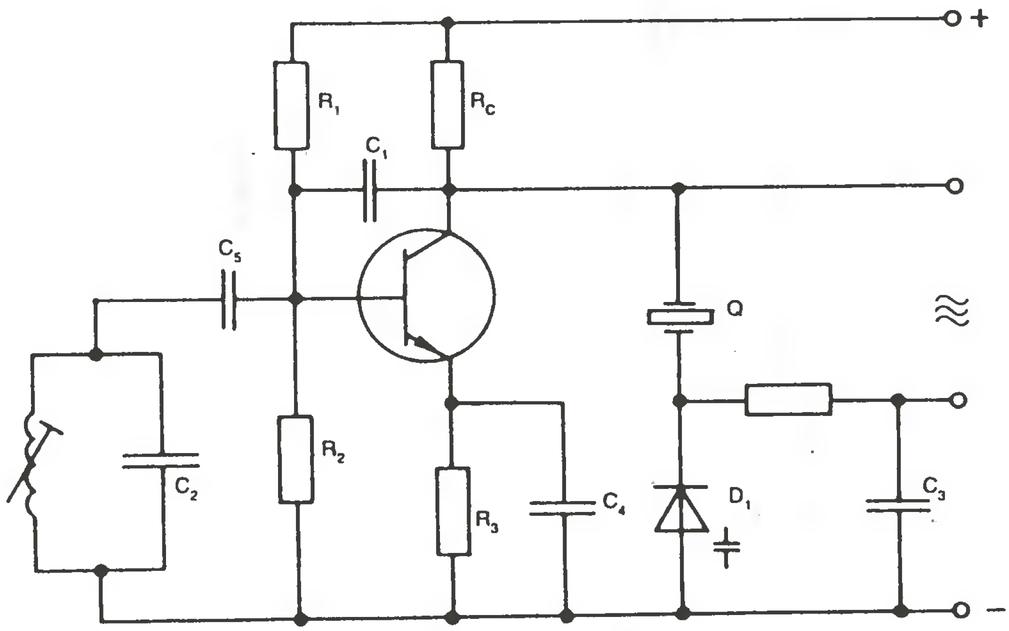


Fig. 3/3.23 g: Quartz oscillator in series resonance. The negative feedback is made across C1; diode D1 carries out an automatic correction of the frequency

Excitation level

This is the maximum power through the quartz crystal which does not cause any deterioration or excessive shift in the frequency. It is normally expressed in microwatts (μW) or milliwatts (mW).

f_0 frequency

This is marked on the casing and is the frequency at which the quartz crystal will function.

Accuracy of specified frequency

The variation in the specified frequency is normally expressed as a percentage of f_0 at 25°C. All quartz crystals are specified as if they are to be used in series resonance. Parallel resonance quartz crystals are used with a trimmer capacitor C_L.

Charging capacity

In many applications, the quartz crystal is tuned to the requirements of the user. In a parallel reactance oscillator, the frequency of the series quartz crystal is trimmed by the capacitive circuit, and the quartz crystal is intended to function with a trimmer capacitor C_L defined as follows:

$$C_L = \frac{C_d \cdot C_g}{C_d + C_g} + C_s$$

C_d and C_g are the capacities of the network between each terminal and earth.

Q factor

This is mathematically defined by:

$$Q = \frac{W \cdot L1}{R1} = \frac{1}{C1 \cdot R1}$$

Generally speaking, the larger that Q is, the more stable the oscillator is. Typical values vary between 2000 and 100 000 or more.

Temperature coefficient

This is the factor which determines the damping of the frequency curve as a function of the temperature. For the majority of applications, a low k value is desirable. Typical values of k range from 0.03 to 0.04 ppm/°C².

Parallel capacitance

This capacitance determines the non-resonant frequency of the quartz crystal and can be measured with a capacitance meter. Typical values of C_o range from 1 pF to 3 pF.

Point of inversion

The ratio between a change in temperature and the frequency is given by the equation:

$$\frac{\Delta f}{f} = k(T_1 - T_2)^2$$

where $k = -0.04$ ppm/°C²

Vibration

The mechanical resonant frequency of quartz crystals is generally between 2000

and 7000 Hz. The mechanical vibration at resonant frequencies can affect the oscillator and cause significant shifts in frequency.

Shocks

Shock tests are frequently carried out by dropping the assembled quartz crystals on to appropriate surfaces (lead or wood), during which the acceleration and deceleration are calculated.

3/3.24

Relays

The relay is one of the oldest electronic components. Its invention dates from the start of the century, and it has developed to a sophisticated level which matches recent electronic developments in pulsed switching, despite considerable competition from solid-state devices.

The essential characteristics of relays are:

- The safety ensured by the electrical isolation between the contacts of the relay and its driving circuit.
- The stability of the relay when subjected to impulse interference and other variations in the supply voltage.

In electronics, the most commonly used relays are non-polarised direct current relays. The principle of the relay is to open and close a series of contacts attached to a movable magnetic core in an electrical coil by exciting or de-exciting the coil.

Several types of contacts can be found on a relay:

- Make-and-break contacts: these "make" or complete the circuit in which they are inserted when the relay is energised, and "break" or open the circuit when the relay is de-energised.
- Break-and-make contacts: these open the circuit in which they are inserted when the relay is energised, and vice versa.
- Changeover contacts which have three contacts, and by suitable wiring reverse the flow of current in a circuit when they are energised/de-energised.

Fig. 3/3.24 b shows the symbols used to describe these different types of relays.

The choice of a particular type of relay for an application is based on the following criteria:

- The control voltage (in general the useful range of voltages is between 6 V and 24 V).
- The power consumed by the coil (this value is necessary in order to calculate the circuitry which will control the relay).
- The maximum value of the current which can pass across the power contacts of the relay.
- The maximum voltage which can be switched by the power contacts.
- The switching capacity of the power contacts of the relay when used in direct or alternating current.

Fig. 3/3.24 c shows a typical application of control by a relay. The coil of the relay is controlled by a transistor. When the transistor is saturated, the voltage V_{CE} approaches 0.6 V; this implies that the relay is "closing" (is energised) because it has the voltage (V – 0.6 volt) at its lower terminal.

3.24 Relays

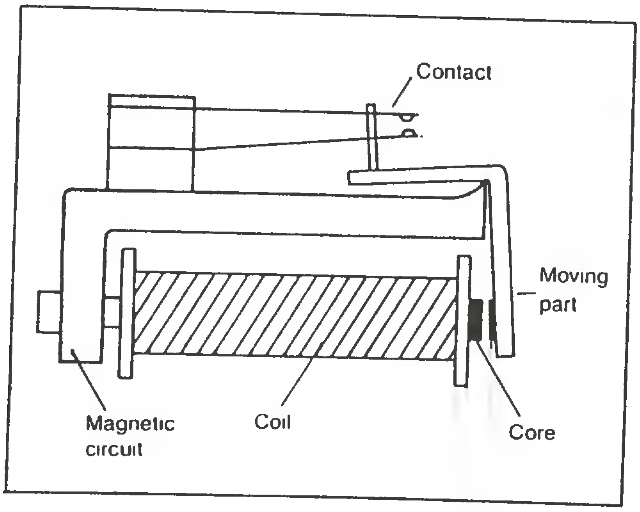


Fig. 3/3.24 a: Diagram of a relay

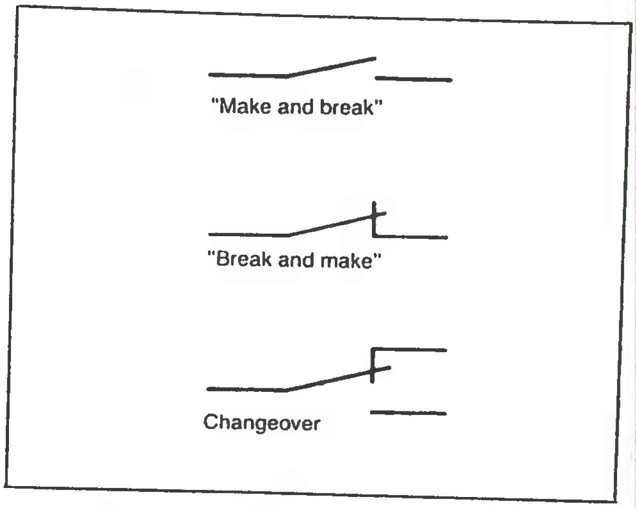


Fig. 3/3.24 b: Symbols used to show the various types of relay

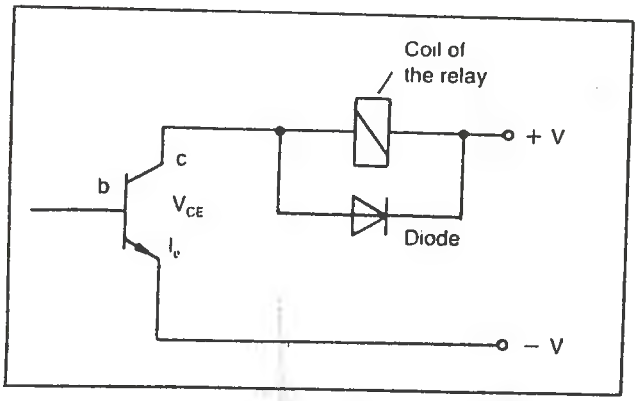


Fig. 3/3.24 c: Circuit diagram of a relay controlled by transistor

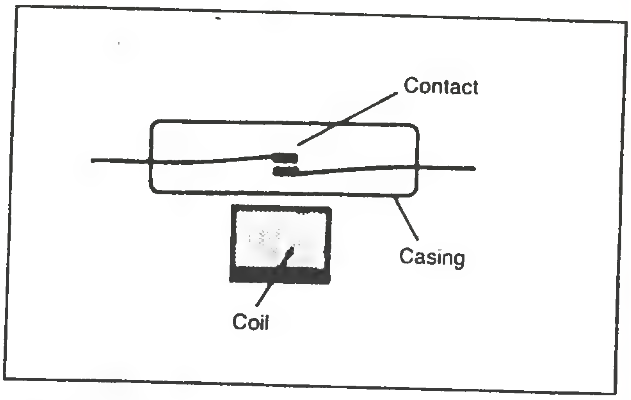


Fig. 3/3.24 d: Reed relay

When the transistor is blocked, V_{CE} is equal to the supply voltage V; in this case, the relay is open. When controlling a relay with a transistor, it is always necessary to put a diode (for example, 1N4148) in parallel with the relay. The function of this is to prolong the life of the transistor because it short-circuits the induced currents which are produced during the de-activation of the relay. These currents create a back e.m.f. which is very hazardous to the "life" of the transistor. It should be realised that the diode does not interfere in any way with the control function of the relay.

Fig. 3/3.24 d shows the circuit diagram of a reed relay. These are frequently encountered in electronics. They generally have a single contact and can be soldered directly on to a printed circuit.

4/2.1

Hand tools for electronic kit building

Whether you are an amateur or master kit builder, the moment of truth comes after all the components are put in place, bolts and screws have been tightened, wires properly soldered, and the final check-out tests completed. Then, as the power is applied and all systems function as designed, a great deal of pride and a sense of accomplishment comes over you.

However, too often the results are not as rewarding. Not using the proper tools and not knowing their proper use can result in damaged components, scratched surfaces, and personal injury.

We will discuss and examine the hand tools most commonly used when building electronic kits.

The basic hand tool set for the electronic kit builder should include:

- Combination Pliers
- Long-Nose Pliers
- Side Cutters
- Blade Screwdrivers, 1/8" and 1/4"
- Phillips Screwdrivers, No. 1 and No. 2
- Nut Driver Set, 3/16" to 1/2"
- Wire Strippers/Cutter
- Pencil Soldering Iron, 25 watts
- Desoldering Tool and Desoldering Braid
- Heat Sink

Pliers

Pliers are made in many styles and sizes. However, all pliers are made of two parts pivoted together to form two handles and two jaws, used to grip or cut objects.

Combination pliers

Combination pliers have a flat jaw at the end and a round open jaw near the pivot point. These pliers are used to hold or bend flat or round stock. Some of these pliers have a slip joint which allows the jaws of the pliers to open wider.

Pliers should not be used to turn nuts. They can damage a nut very quickly, making it difficult to get the nut loose. Use a nut driver or spanner to turn nuts.

Long-nose pliers

Long-nose pliers are commonly called needle-nose pliers. They are excellent for holding small objects, making delicate adjustments, and forming wire loops and bends. Long-nose pliers come in a variety of shapes and sizes. Some of the smaller pliers will have a spring action allowing the jaws to open.

A convenient size of long-nose pliers to have is a 4-3/4" or 6".

Do not make pliers work beyond their capacity. Long-nose pliers can be easily

2.1 Hand tools for electronic kit building

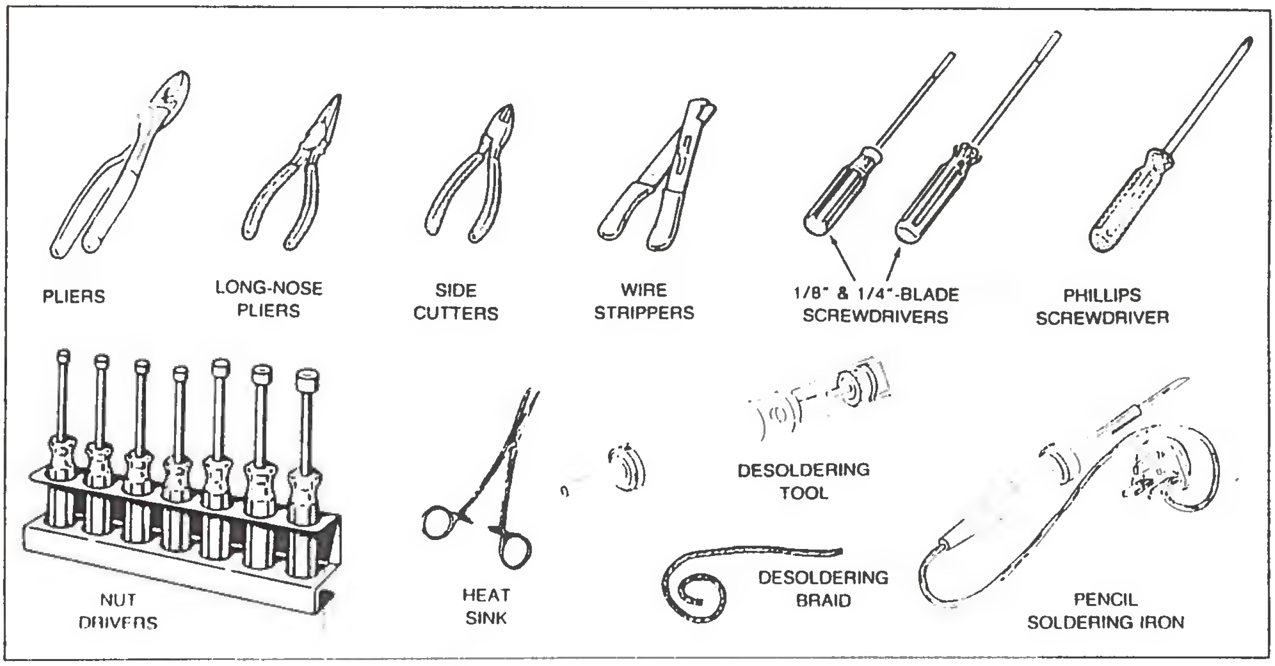


Fig.1: Basic tool set

sprung when too much pressure is exerted.

Side cutters

The jaws on side cutters run at diagonals to each other forming a sharp cutting edge. These pliers are used to cut wire. They are not designed to be metal or tin snips. After considerable use, it may be necessary to file the burrs that may occur on the cutting edges.

A good size to have for small work is a 4-1/2" or 6".

Screwdrivers

The screwdriver is one of the most basic hand tools. It is also one of the most misused tools. It is designed to drive and remove screws. It should not be used as a pry bar or punch.

All screwdrivers consist of three main parts.

1. Handle – the part you grip with your hand.
2. Shank – the steel portion extending from the handle.
3. Tip – the end of the shank that fits into the screw head.

Handles are generally made of an insulating material such as wood or plastic. Metal handled screwdrivers are not recommended for building or working on electronic kits.

Shanks are square or round and are designed to withstand considerable twisting force. Square shanks are designed

for heavy-duty work and can be gripped with a wrench. Shanks come in various lengths.

Tips of screwdrivers are either a flat blade or have a four-way slot for Phillips head screws.

Caution: Do not hold work in your hand whilst using a screwdriver. If the point slips it can cause injury. Your work should be held in a vice or secured on a solid surface. A good rule to remember is: NEVER GET ANY PART OF YOUR BODY IN FRONT OF THE SCREW-DRIVER TIP.

Screwdrivers have a tendency to become magnetized. This can cause serious problems to some integrated circuits if the screwdriver comes in close proximity of the ICs. Periodically demagnetize your screwdrivers.

Flat-blade screwdrivers

The most common size blade for working on electronic kits are 1/8" and 1/4". Use a screwdriver blade that fits the slot in the screw. Do not use an undersize blade on a large slotted screw. Damage will occur to both the screwdriver tip and the screw head.

Phillips screwdriver

Phillips screwdrivers required for most work come in two sizes. The smaller tip is a No. 1, and the larger tip is a No. 2.

Nut drivers

Nut drivers are used to tighten or loosen nuts. They are similar to a screwdriver except the tip has a hex head on it to wrap around the nut. Place the nut driver on the nut and turn.

A set of nut drivers should range in sizes from 3/16" to 1/2", and a metric set is also useful.

Wire stripper/cutters

Wire stripper/cutters have the characteristics of a pliers except the jaws are designed to remove insulation from wire. Most are adjustable to strip insulation from 12 to 24 gauge wire.

Place the cutting notches of the wire strippers around the wire insulation to be removed. Squeeze the handles together enough to just cut the insulation. Then slide the insulation off the end of the wire. To cut light gauge wire, place the wire on the cutting edge and squeeze the handles together until the wire is cut. For heavier wire, use diagonal cutters.

Soldering tools

Soldering Iron

A low wattage soldering iron of about 25 watts should be used on all electronic devices. A high wattage soldering iron may cause permanent damage to foil traces on a circuit board and to sensitive components. DO NOT use a soldering gun on electronic circuits. The strong electromagnetic field surrounding the tip of the soldering gun could cause serious damage to electronic components.

For efficient heat transfer in the soldering

iron, keep the tip of the soldering iron securely fastened to the heating unit and keep the shaft and tip clean.

Desoldering tool

A desoldering tool removes molten solder from circuit connections allowing components to be removed without damage. A spring loaded piston is compressed, while solder is melted, then released by a push button creating suction at the tip. Reloading the piston then pushes the old solder out of the tip. The tip which is made of high temperature plastic can be removed for cleaning and replacement.

Desoldering braid

A desoldering braid or soldering wick, is used to remove solder from circuit connections. Place the braid on the connection where the solder is to be removed. Then heat the connection and braid with a soldering iron. The excess solder will flow up the desoldering braid.

Heat sink

Heat sinks are designed to keep damaging heat away from a component while making soldering connections. There are many styles of heat sinks available. The locking clamp style works very well and also serves as a convenient tool for holding small parts.

However, provided that your soldering technique is neat and fast, most modern components do not require the use of a heatsink.

Summary

Before beginning a project, lay out all of the tools you will need to use. Do not use broken tools. Be sure all tools are clean and in proper working condition. When storing tools, wipe a light oil film on all metal parts. Always follow the manufacturer's recommendations for safety and use.

As a general rule when purchasing tools, you get what you pay for. Less expensive tools tend to break, strip, or wear out faster than the brand name and the more expensive tools.

4/2.2

Electrical soldering techniques

Soldering was performed by the Romans as early as 3000 B.C. Silver solder was first used to decorate vases and other art objects. Later, it was discovered that a soft soldering process could be used by combining lead and alloys of lead. The Romans began the first public water system by soldering together many pipes which were used to transport water over great distances.

During the early 1900s, the introduction of the tin can brought about the use of solder as an alloy of tin and lead. Combining the correct amounts of tin and lead made soldering tin cans very economical and practical.

In recent years many advances have been made in the sciences of soldering, fluxes, and the application of soldering. However, the basic fundamentals of soldering still remain the same.

The importance of good soldering habits can not be overemphasized. Every day millions of soldering connections are made in products that affect our lives and the way we live. The space program, computers, television, radio, and life-saving medical equipment are just a few of the areas where soldering occurs.

In this article, you will learn about metal characteristics, solder, fluxes, soldering irons and guns, proper soldering techniques, and some safety precautions.

Take time to learn and understand these processes. If you have experience in soldering, this article will provide you with a good review and a better understanding of basic soldering principles.

Remember, poor solder connections are costly. It takes no longer to make a good solder connection that it does a poor connection. Perfect your soldering skills and you will insure your success in assembling electronic equipment.

Metal characteristics

Atomic structure

The metal atom has many free electrons in its outer orbit. These free electrons easily interchange with free electrons of nearby atoms. This electron attraction creates a strong bond, making metals a solid material. This same movement of electrons also allows metals to transfer electrical current.

Alloys

Alloys are made up of two or more different elements, and at least one must be a metal. Solder, for example, is an alloy of tin and lead. Both of these metals have a lower melting temperature than most other metals. This makes solder a convenient alloy to join other metals together.

2.2 Electrical soldering techniques

Soldering theory

Wetting

When solder melts into a liquid state and comes in contact with another metal, the molecules of solder flow or wet over the metal being soldered, interacting with the free electrons in the outer orbit of the base metal. The molecules of solder actually bond with the molecules of the wire and base metal being soldered. This process is known as "wetting".

After the solder cools, a strong molecular, mechanical, and electrical connection is made. This bonding action is only about one molecule thick but is sufficient to provide a good electrical and mechanical connection. Refer to Fig.1.

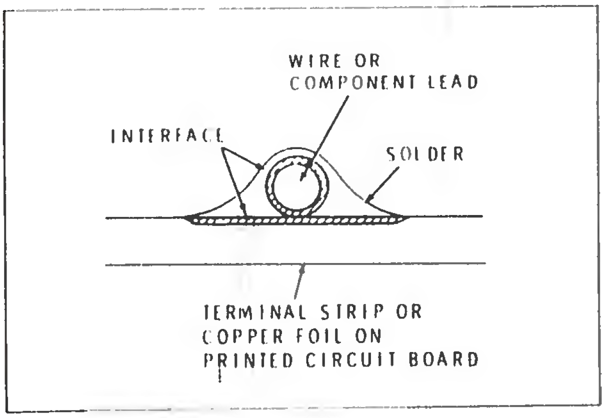


Fig.1: Process of soldering

Two important factors should be considered in any electrical connection. First, a strong mechanical connection must be made between the wires or metals to be soldered. Second, a good soldering connection must be made to provide a low resistance connection and to provide additional mechanical strength. This results from good wetting and bonding.

Solderable metals

Only certain metals are atomically structured to accept wetting by a tin-lead alloy solder. Of these metals, copper is most commonly used and is the easiest to work with. Other solderable metals are silver, iron and steel, zinc, nickel, gold, platinum, and palladium. Some metals are solderable using special alloys and fluxes. These include aluminium, stainless steel, and magnesium. There are a few metals which are almost impossible to solder. They are cobalt, chromium, and silicon.

Solder alloys

An alloy is a mixture of two or more different metals. Tin and lead are the two metals used to make up solder.

Alloys retain most of the characteristics of the original metals when they are mixed with other metals. However, there may be a change in the melting temperature, a change in hardness, and a difference in the wetting ability. Solder is ideal for joining electrical parts because it melts at lower temperatures than most other metals.

The corrosion resistance of tin permits it to be used as a coating on copper wire leads for protection against corrosion caused by air and water.

The surface of lead corrodes quickly and acts as a barrier to further corrosion below the surface.

Tin bonds with metals easily. But the melting temperature is too high. However,

lead reduces the melting temperature and, when mixed with tin, it adds to the overall strength.

Solder is expressed as a ratio of tin and lead. The first number represents the percentage of tin. The second number represents the percentage of lead in the alloy. As the ratios change, so does the melting temperature. The eutectic ratio 63/37 has the lowest fusing or melting temperature. But because of its higher tin content it is more expensive.

When solder is heated and then cooled, it passes from a liquid state to a pasty condition then to a solid state. The eutectic-ratio solder changes from the liquid state to solid without passing through the pasty stage, making it the ideal type of solder. Without going through the pasty stage there is no need to worry about keeping the solder joint perfectly still until the solder cools. A 60/40 ratio solder is the most popular solder to use. It is less expensive than the V63/37 solder and its liquid temperature is very close to the eutectic-ratio solder.

Some of the tin/lead ratios of solder and their properties are listed below.

- 70/30 Good for pretinning; expensive
- 63/37 Eutectic solder; no pasty state; best solder
- 60/40 Good general purpose solder
- 50/50 Lower-cost general purpose solder
- 40/60 Lowest-cost common solder

The characteristics of solder can be changed by adding small amounts of different metals to the tin/lead mixture. For example, adding antimony hardens solder. Small amounts of copper reduce the pitting of copper tips on soldering irons. The addition of bismuth increases the wetting ability, and adding gold or silver retards the reduction of silver or gold from connections plated with these metals.

Solder qualities

The ideal solder should have the following qualities for the best performance:

Wetting. Have good capillary action in flowing over the base metal, bonding, or alloying with its surface at every point, including the crevices between wire strands and terminals.

Temperature. Be able to reach the liquid state and wet the base metal at as low a temperature as possible, consistent with its other qualities. Minimum temperature means least possible damage to the terminals or the components being soldered.

Strength. As hard as possible consistent with other qualities. Must be free of brittleness, have a minimum coefficient of expansion compared with the base metal and low creepage.

No solder is perfect in all these requirements, but modern alloys are allowing us to come closer to these standards.

Flux

Two conditions must be met when soldering. The items being soldered must be heated to the point where the solder will

melt and flow over the metals being soldered. The second is the metal being soldered must be clean and free from all dirt, grease, and oxide.

The condition of oxidation occurs when copper is exposed to oxygen in the air. A thin layer of oxide will cover the wire which prevents solder from wetting and adhering to the metal.

Flux is used to remove this oxide coating. When flux is heated, it chemically eats away the oxide and cleans the surface, allowing solder to flow and bond properly.

Remember, flux removes only oxide. It will not remove any dirt, grease, or other foreign material that may be present.

Flux core solder

Most solders used in electronics have flux built into the core of the solder wire. In this way, cleaning and soldering occur almost simultaneously. Different manufacturers use different additives to make the flux more active. The type of core the solder has also varies with the manufacturer. Fig.2 shows a cross-sectional view of three types of flux cores. The most popular solder is the inner core.

Soldering irons

The growth of electronics caused the soldering iron industry to keep pace with the new technology.

The evolution of soldering iron covers; gasoline torch heated irons, internal electrically heated irons, improvements in construction and tip life, and pencil size low-wattage irons. Refer to Fig.3.

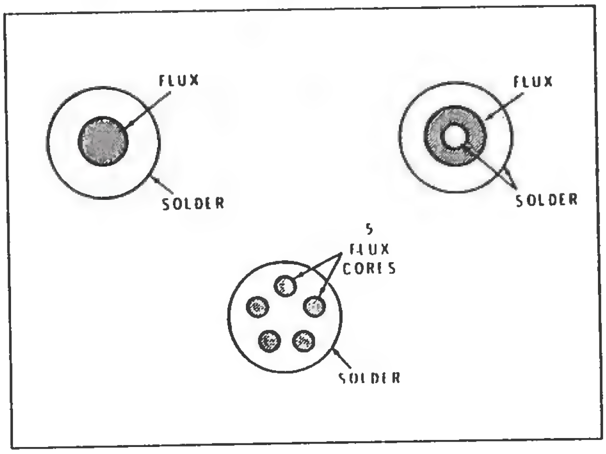


Fig.2: Cross-sectional view of solder

Construction

The soldering iron is made up of three main parts: tip, heating element, and handle.

Tip – The part that transfers heat from the heating element to the piece being soldered. The tip is usually made of a copper rod shaped into a point or blade. Many shapes of tips are available for different soldering applications. Most irons have replaceable tips that screw into the heating element. Fig.4 shows some of the soldering tips that are available.

Heating Element – It is made up of a coil of nichrome wire, insulated from but wound around the inner core of copper. The heat of the coil is carried by the copper core to the tip. Some heating elements are interchangeable and screw into the base handle. Refer to Fig.4.

2.2 Electrical soldering techniques

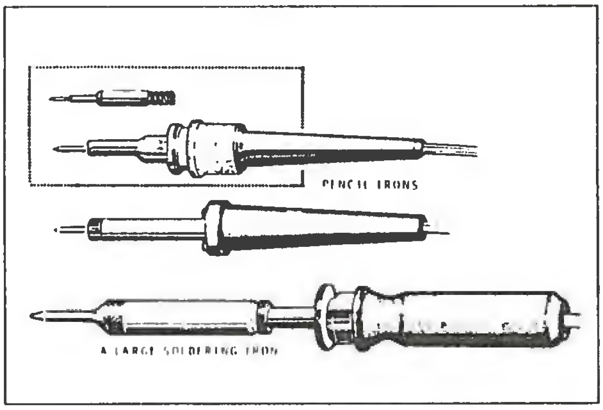


Fig.3: Popular types of soldering irons

Handle – It is designed to remain cool and be balanced and lightweight. A power cord is chosen for the low amperage rating iron.

Pencil Irons

A large soldering iron is very difficult to use on printed circuit boards having small components. This type of circuitry gave way to the development of smaller, lightweight, easier to hold, lower in power, miniature irons using smaller tips.

Transformer-isolated irons

Some high-impedance semiconductors are extremely sensitive to static electricity. Even static electricity picked up by the human body can destroy some semiconductors.

The need to protect these high-impedance transistors resulted in the development of a soldering iron that works at lower voltage and from an isolation transformer. Voltages of 12 and 24 are commonly used. The transformer isolates the soldering iron

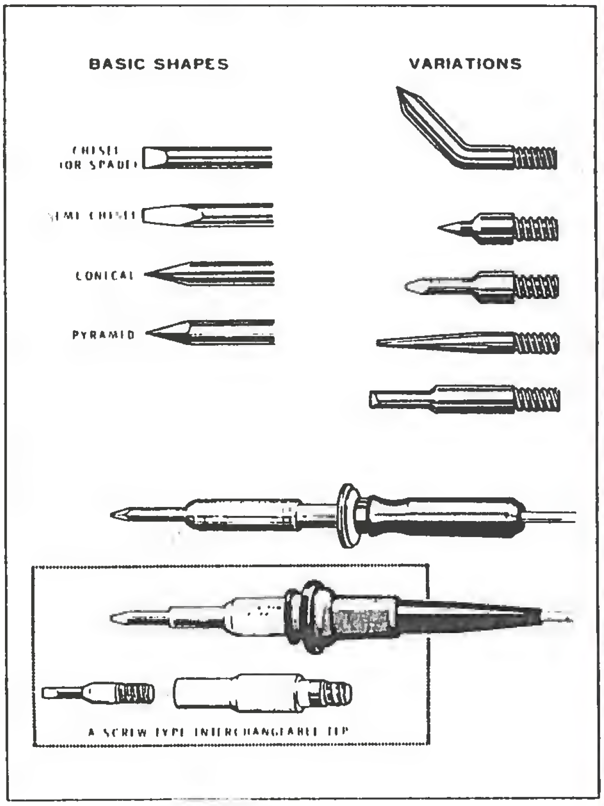


Fig.4: Soldering iron tips

from the 240 V AC line. This reduces possible damaging line surges from reaching the transistor whilst it is being soldered.

Tips

Most soldering irons have replaceable tips. Exceptions are the very inexpensive soldering irons where nothing is replaceable and they are basically a "throw-away unit".

Tips in most of the larger irons are a solid copper shank held in place by set screws or nuts. Most miniature-irons with replaceable tips use the screw-in type.

One reason for tip replacement is to install a new tip when the old tip wears out. The soldering iron has almost indefinite life. However, tips are subject to oxidation and corrosion. Another reason for tip replacement is to switch tips to match the work you are soldering.

Tip care and retinning

Corrosion on the soldering tip acts as a heat insulation barrier and prevents proper heat transfer from the iron to the connection being soldered. As we mentioned before, copper tips exposed to air will oxidize. Keeping the soldering tip coated or tinned with a light coat of solder, keeps oxidation build-up to a minimum. With a properly tinned tip, maximum heat transfer is insured.

To properly prepare and tin a soldering tip, the tip must be cool. Then, place the tip of the iron in a vice and file the soldering surface clean until all corrosion is gone. Use a fine emery cloth to buff the surface and to remove any burrs that may be present.

The tip is now ready for tinning. As soon as the tip begins to heat, oxidation will begin. Therefore, it is important to tin the tip as quickly as possible to keep oxidation to a minimum.

Plug the soldering iron into the power receptacle and wait about 60 seconds. Then, begin applying flux core solder to the tip. The iron may not be hot enough to melt the solder, but keep applying the solder. Very shortly the solder will melt and cover the tip. Remove the solder and unplug the soldering iron.

When excess amounts of solder accumulate on the tip, it should be wiped off with a wet cellulose sponge. When the iron is laid aside for awhile but kept hot, the tip should have extra solder on it, or the normally thin layer will oxidize off while the iron is idle.

Never file down iron-clad tips. They resist corrosion better than copper tips and it should only take a few swipes of emery cloth to clean these surfaces.

Instant heat guns

Soldering guns are so named because of their shape and resemblance to a gun. A typical soldering gun consists of a handle, trigger, and tip. Refer to Fig.5.

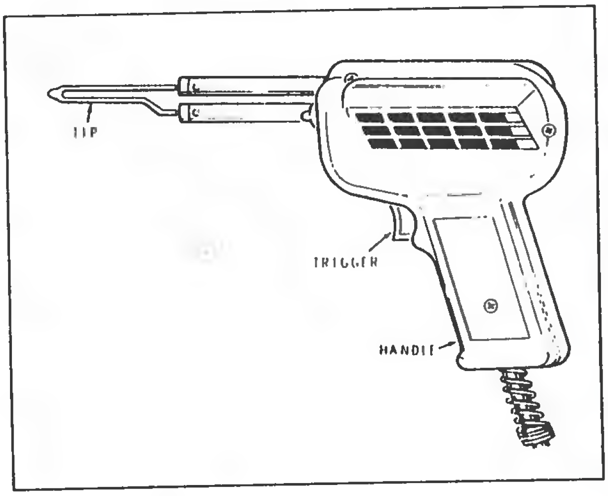


Fig.5: Typical soldering gun

Soldering guns heat up in about 3 to 5 seconds. This is accomplished by using a step-down transformer inside the soldering gun. The AC line voltage is stepped down to a low voltage that is high current. This high current is passed through the soldering

2.2 Electrical soldering techniques

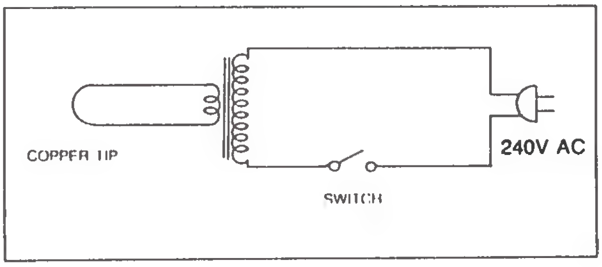


Fig.6: Instant heat gun circuit

tip which serves as a single coil secondary winding of the transformer. Refer to Fig.6. Some soldering guns have a multiple-position trigger switch that controls the amount of heat produced.

The advantages of soldering guns are the instant heat and the larger amounts of heat they can produce. This is very important when soldering heavy wire and connections. Most guns are well balanced, making them easy to use.

The disadvantages of soldering guns are: the internal transformer makes them heavier than a soldering iron, the high heat they produce can damage sensitive component and foil traces on circuit boards, and a strong magnetic field is generated at the secondary coil or tip which will cause damage to some integrated circuits.

Self-regulation

Copper has a high coefficient of expansion. When power is first applied to the soldering gun, current in the soldering tip is quite high. However, as the tip heats up, the current through it drops because the resistance increases with the heat. As the tip is touched to the connection being soldered, some of the heat is removed from the tip. The tip becomes cooler, its resistance decreases, and the current increases causing more heat.

How to solder

Now that we have some knowledge of soldering principles, it's time to put these ideas to work. Soldering as we have learned is a process of joining mechanically and chemically two or more materials.

In our application, we will be soldering electrical components, wires and printed circuit boards. This process involves a combination of two main procedures: mechanical and chemical.

But first you must choose the proper tools for the job.

The right iron and tip

Many styles of soldering irons are available. Choose a low-wattage iron (about 25 W) for printed circuit work and one that will fit comfortably in your hand.

When soldering, it is very important to transfer heat as quickly as possible. The tip contour must be such as to provide maximum surface contact to the connection. There are many shapes of tip available. You may find it helpful to have a selection of tips on hand so a shape can be found to meet your specific need. The most popular tip shapes are the point and the blade style.

Be sure the tip is always clean and well tinned.

2.2 Electrical soldering techniques

Solder and flux

Except for special applications, soldering should be accomplished with flux core solder of a 60/40 or 63/37 tin/lead ratio. The 63/37 ratio is the eutectic ratio. This means solder goes from a liquid to a solid without passing through the pasty stage. The ratio of 60/40 is so close to the eutectic ratio that the pasty stage does not create a problem.

Flux-core solders come in different diameters. Size 20 or 0.036" is very good for printed circuit board work. Size 16 or 0.064" is larger and feeds slower. Because it is heavier, you may find it easier to handle. Always use flux-core solders on electrical components.

Cleanliness

To make a proper solder connection, the wire leads and terminals must be clean. Flux cleans the oxide coating during the soldering process. However, flux will not remove grease, paint, and heavy corrosion; this must be done by hand. For solder to wet properly, the metals must be clean and bright.

Handle components and circuit boards by their edges to keep your fingers off the wire and circuit traces. Oil from your fingers can affect the wetting process.

Clean dirty leads and contacts with a fine emery cloth. After cleaning the connections, be sure to remove any dust that may have been generated.

Wire stripping

The ends of wire need to have the insulation removed so they can be soldered or otherwise connected to a circuit. It will be worthwhile to invest in a wire stripper, which is a device that holds the wire behind the part to be stripped and then uses a pair of claws to cut the insulation and pull it away from the wire.

Insulation can also be removed with a knife. Or, the use of diagonal cutters works very well too. Just cut a circle around the insulation with the cutter; then, with the cutters jaws in the circle, pull the insulation off the wire.

Insulation should be cut back about 1/8" beyond the point of solder. If the insulation is too close to the solder connection, some of the insulation material could melt into the connection and prevent good wetting. If it is cut too far away, the possibility exists of the exposed wire causing shorts.

Tinning lead

It is a very good practice to tin the ends of stranded wires. Tinned wires make inserting the wire ends into printed circuit board holes and around terminal connections much easier. This also insures that no loose strands of wire are free to cause a possible short circuit. At the factory, wire ends are dipped in a liquid flux then into a pot of molten solder.

To tin wires for non-production procedures, the process is easy. First, strip the insulation from the end of wire, then, with your fingers, twist the strands of wire

tightly together. The best way to tin the wire end is to have the soldering iron lay on the bench or secured in a vice. Then with wire in one hand and solder in the other, place the wire on top of the hot soldering iron tip, then apply the solder to the top of the twisted wire. The melted solder will flow through the strands of wire.

Soldering practices

To make a proper solder connection, the connection must be mechanically sound. But this by itself will not make a good electrical connection as it can result in a high-resistant connection. The wires or connections must be chemically fused together. This is accomplished by heating the connection and applying solder to fuse the connection. Solder adds mechanical strength to the connection as well as providing an excellent low resistant permanent electrical connection.

Mechanical connections

When soldering a component to a terminal, use a needle-nosed pliers to bend the lead around the terminal before soldering it. This insures a strong mechanical connection and keeps the wire from moving while soldering.

Printed circuit boards

Printed circuit boards consist of a sheet of phenolic laminated with a sheet of copper. The circuit is then printed, screened, or photographically applied over the copper sheet on the circuit board. The board is then dipped in an acid solution where the exposed copper is removed leaving only the printed circuit.

Resistor mounting

When mounting resistors on a circuit board, press the resistor leads through the circuit board hole until the body of the resistor is against the circuit board, then bend the leads over on the foil side to hold the resistor in place. Refer to Fig.7.

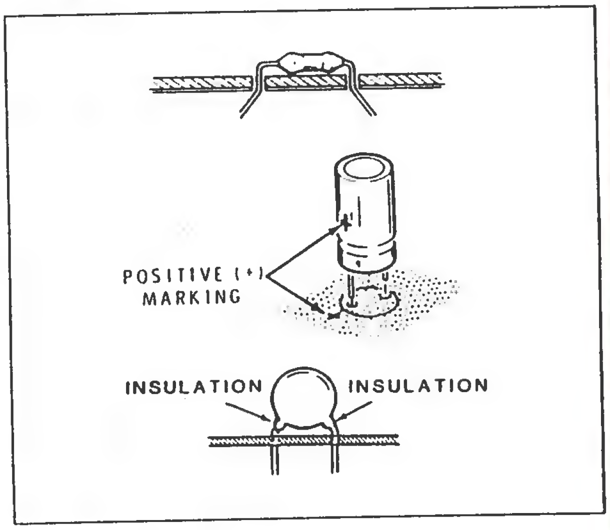


Fig.7: Mounting resistors, electrolytic and disc capacitors

Capacitor mounting

When mounting electrolytic capacitors to a circuit board, keep the body of the capacitor about 1/8″ from the circuit board. Refer to Fig.7.

When mounting disc capacitors, do not push the insulated portion of the leads into the circuit board holes. This could make it difficult to solder the leads to the foil. Refer to Fig.7.

Transistor mounting

To prepare a transistor for circuit board mounting, bend the centre lead back as shown in Fig.8.

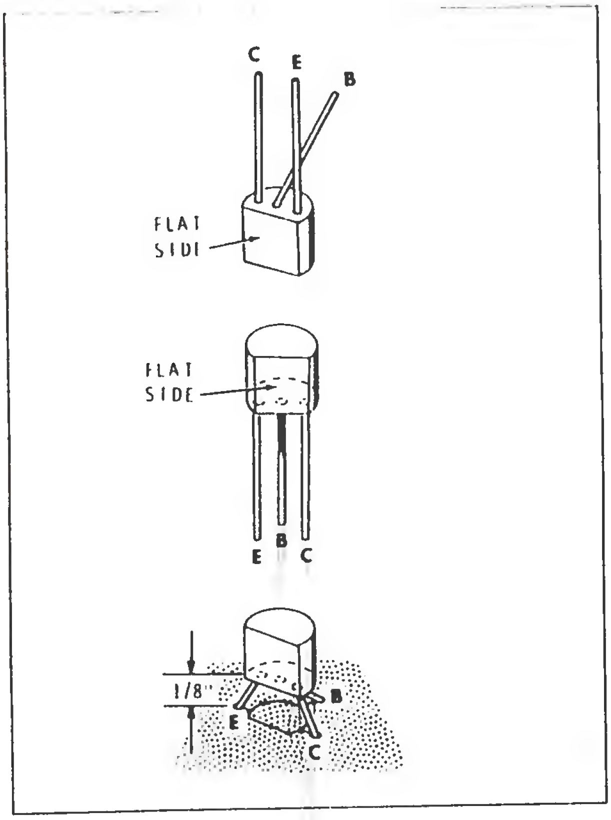


Fig.8: Mounting a transistor

With the flat side of the transistor and the emitter, base, and collector properly lined up with their respective holes, press the transistor into position. Keep about 1/8" between the board and the transistor. Refer to Fig.8. Bend the leads back slightly on the foil side to hold the transistor in place.

Excessive heat will destroy semiconductors. When soldering, place a heat sink on the lead being soldered. Inexpensive commercial heat sinks are available. Or, an alligator clip pulls heat away from the semiconductor keeping it protected from heat. When soldering a semiconductor, place the hot soldering iron so it makes contact with the foil and the lead for about 3 seconds. Then touch the connections with solder. As the solder melts, remove the solder and the soldering iron. After the connection cools, remove the heat sink and clip off any excess leads.

Soldering components

Press the tip of a heated soldering iron against both the lead and the circuit board foil. Heat both for about three seconds. Refer to Fig.9A.

When the connection is hot, apply solder to the other side of the connections as shown in Fig.9B. Note: Let the heated lead and the circuit board foil melt the solder.

As the solder begins to melt, allow it to flow around the connection. Then, remove the solder and the iron and let the connection cool. Refer to Fig.9C.

After the connection cools, cut off the excess lead lengths. Use caution to protect your eyes as lead clippings will fly through the air.

Check the solder connection for a shiny and smooth look. Also, be sure no solder bridges were made. Solder bridges occur when solder flows from one terminal to another. Refer to Fig.10. This condition will cause a short circuit. It must be corrected. Removing solder bridges are

2.2 Electrical soldering techniques

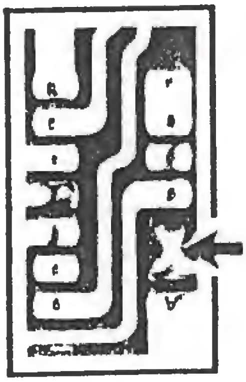


Fig.10: Soldering bridges

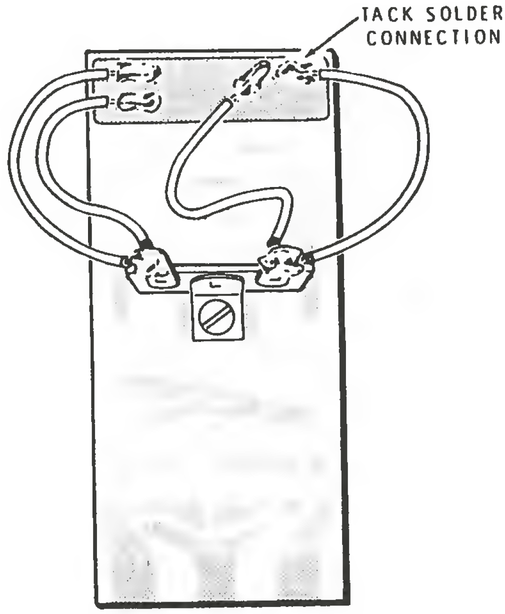


Fig.11: Tack soldering connections

Tack soldering

Sometimes it is necessary to make temporary solder connections and you don't want to bend the wire ends or you don't want to fill up a terminal. The procedure to do this is known as tack soldering.

To tack solder a wire or component, strip the insulation from the end of the wire and tin the lead.

Soldering is easier if solder is first applied to the terminal being soldered and the wire is tinned. This way no additional solder is required.

Place the tinned lead against the terminal. To solder, place the soldering iron against the lead. Be careful not to move the lead until the solder has cooled. Check the connection. If it looks dull, coarse, and crumbly, it is probably a poor connection. Resolder the connection. Refer to Fig.11.

Inspection

After soldering, check all soldering leads. They should have a smooth and shiny appearance. They should not have the look of crumbly or blob solder. Refer to Fig.12 for terminal connections and to Fig.13 for circuit board connections.

Inspect the soldered side of the circuit board for solder bridges. They must be removed.

With careful heating using the soldering iron, the bridge will sometimes split apart, otherwise use a desoldering tool, to suck away the excess solder, then redo the joint.

2.2 Electrical soldering techniques

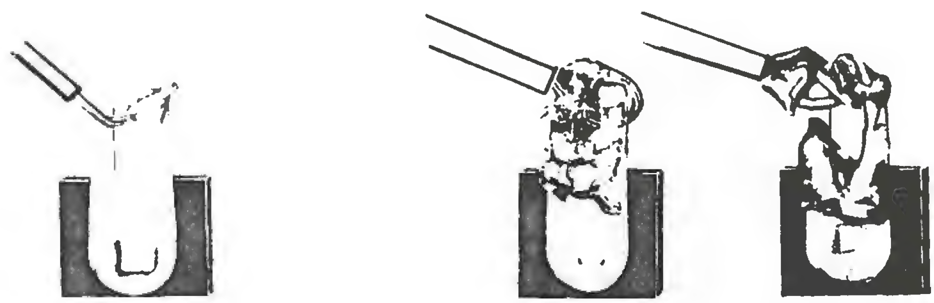


Fig.12: Good and poor terminal solder connections

Fig.13: Good circuit board connections

Safety

Treatment of burns

Since you are working with a hot iron, there is the possibility of touching the iron and receiving a burn.

First aid treatment of burns involves two things: reduce the pain, and prevent infection. ONLY SUPERFICIAL BURNS can be treated locally. Burns that develop blisters or deep burns where whole thicknesses of skin are destroyed should be promptly treated by a physician. Nothing but cold water should be put on the burn, as first aid.

Small burns showing only unbroken skin need very little treatment. Place damaged part under slow running cold water for about 10 minutes or until pain ceases. DO NOT APPLY lotions, ointment or dressings to the damaged area.

Soldering stands

Use a soldering iron stand that is fastened to the bench or that is sufficiently weighted. Return the soldering iron to the stand during all stand-by periods. This

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will reduce the chance of personal injury or damage to miscellaneous equipment on the bench or work area.

Protect your eyes

When desoldering be careful not to get solder in your eyes.

When trimming wire ends from leads, be careful. These leads can fly off like projectiles and can cause serious eye injury.

Summary

Solder is made up of tin and lead alloys. The percentages of alloy used changes the characteristics of the solder. The ideal solder tin/lead ratio is 63/37. This is an eutectic solder, which has no pasty state. The tin/lead ratio of 60/40 is very close to the eutectic solder and is much more economical.

Solder used for electronic circuit work has flux added into the core of the solder wire. This flux cleans the oxide from the metal being soldered. For a good solder joint to be made, both metals must be clean. Enough heat must be used to heat both metals so solder will melt and flow easily over the connection.

A process known as wetting occurs when the molecules of solder mix with those on the surface of the metal being soldered. The solder actually bonds itself with the metals being soldered.

A good solder connection should be smooth and shiny. A bad or cold solder connection looks dull, rough, and crumbly.

The soldering process is easy.

1. Wipe the tip clean.
2. Place the tip against the lead and terminal being soldered.
3. Apply solder to the side opposite the lead from the soldering iron.

Remember, it takes no longer to make a good solder connection than it does to make a poor connection.

4/2.3

Component handling

As the electronic age continues to grow, so do the number of new products and electronic components. More complex electronic kits are becoming available and computer user's are upgrading their own computers with a variety of chips and boards. It becomes increasingly important that you be able to identify electronic components and know how to handle them properly.

In this article, we will cover some of the most commonly used components, their schematic symbols, how to identify their value, and the proper handling of them.

Resistors

Resistors are made of a material that has a specified resistance, or opposition to the flow of electrical current. Resistors are used to control or limit the amount of current flowing in a circuit or to provide a voltage drop.

The schematic symbols for resistors are shown in Fig.1.

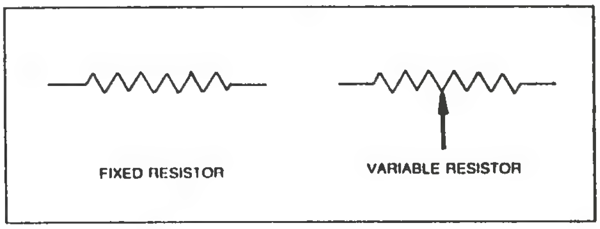

Fig.1: Resistor symbol

There are two basic types of resistors, fixed resistance and variable resistance. Most fixed resistors are made of carbon. The unit of resistance is the ohm. The resistance value of a fixed carbon resistor is coded using coloured bands, although some resistors have their value printed on the side. The chart in Fig.2 shows the values of the coloured bands.

For example, if the coloured bands were: red, green, orange, and no 4th band.

The first band, red, is 2.
The second band, green, is 5.
The third band, orange, is 1000.
The resistor value is $25 \times 1000 = 25\,000\ \Omega$

Since there is no fourth band, the tolerance is $\pm 20\%$ of $25\,000\Omega$.

Installation

When installing a resistor to a circuit board, bend the leads at 90 degree angles to the body of the resistor. Insert the leads into the circuit board holes and press down until the resistor body touches the circuit board. For resistors that have their values printed on them, install these resistors so the values can be read after they are installed.

Capacitors

A capacitor is a device consisting of two

2.3 Component handling

Band Colour	1st Band	2nd Band	3rd Band Multipler	4th Band Tolerance
Black	0	0	1	–
Brown	1	1	10	–
Red	2	2	100	± – 1%
Orange	3	3	1,000	± – 2%
Yellow	4	4	10,000	± – 3%
Green	5	5	100,000	± – 4%
Blue	6	6	1,000,000	–
Violet	7	7	10,000,000	–
Grey	8	8	100,000,000	–
White	9	9	–	–
Gold	–	–	.1	± – 5%
Silver	–	–	0.01	± – 10%
No colour	–	–	–	± – 20%

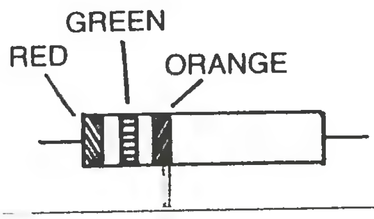

Fig.2: Resistance chart

conducting surfaces separated by an insulating material or dielectric such as air, paper, mica, glass, plastic film, or oil. A capacitor stores electrical energy, blocks the flow of direct current, and permits the flow of alternating current to a degree dependent essentially upon the capacitance and the frequency.

The schematic symbols for capacitors are shown in Fig.3.

Fixed capacitors are divided into different categories based on the type of material the capacitor is made of and the dielectric used. Several styles of capacitors are: paper, ceramic, mica, and electrolytic.

Capacitor values are rated in microfarads or picofarads. The chart in Fig.4 shows how to read the printed value on capacitors.

For example, the value 151 printed on a capacitor reads:

The first digit of the capacitor value is: 1
The second digit of the capacitor is: 5
The third digit is the multiplier, which is: 1

Multiply the first and second digits by the value assigned to the multiplier.

Example: 151 = 15 × 10 = 150 microfarads.

2.3 Component handling

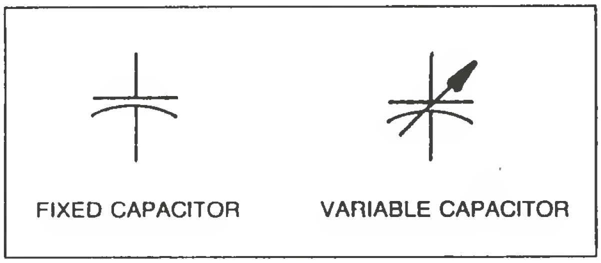

Fig.3: Capacitor symbols

First & Second Number of	Third Number:	Multiply by:
--	0	1
--	1	10
--	2	100
--	3	1000
--	4	10,000
--	5	100,000
--	8	0.01
--	9	0.1

Fig.4: Capacitance chart

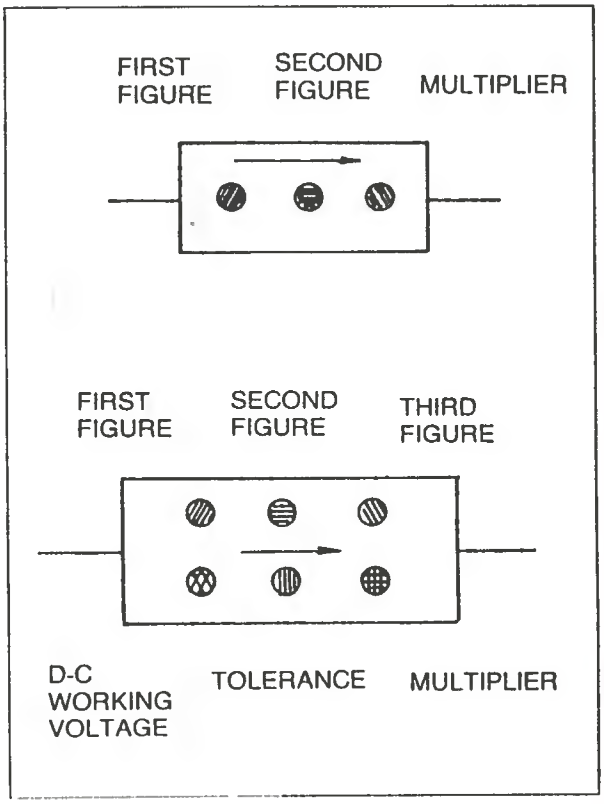

Fig.5: Mica capacitor

Another method of coding capacitor values uses colour dots. Fig.5 shows mica capacitors with three and six dots.

The chart in Fig.6 provides the colour code to read the capacitance value of mica capacitors coded with dots.

For example, if the colour dots are red, green, or brown:

The first dot is red, 2.
The second dot is green, 5.
The third dot is brown, 2.

The capacitor value is 25 × 10 = 250 picofarads or .00025 microfarads.

Installation

Capacitors are normally installed horizontally to the circuit board. Occasionally you will be requested to install it in the vertical position.

Some capacitors have the polarity marked using a (–) for negative and (+) for positive. The negative side my have a solid band around it. Be sure when installing a polarized capacitor to make sure the correct polarity connection is made.

When installing a capacitor, bend the leads at 90 degree angles to the capacitor. Insert the leads into the circuit board holes

2.3 Component handling

Colour	Figures	Multiplier	DC Working Voltage	Tolerance
Black	0	1	---	---
Brown	1	10	100	1%
Red	2	100	200	2%
Orange	3	1,000	300	3%
Yellow	4	10,000	400	4%
Green	5	100,000	500	–
Blue	6	1,000,000	600	6%
Violet	7	10,000,000	700	7%
Grey	8	100,000,000	800	8%
White	9	1,000,000,000	900	9%
Gold	–	0.1	1,000	5%
Silver	–	0.01	2,000	10%
No colour	–	---	500	20%

Fig.6: Mica capacitor code chart

and press the capacitor down until the capacitor touches the circuit board. Keep the side of the capacitor showing its value, facing up.

For vertical mounting, insert the one lead through the circuit board hole and press the capacitor down until it makes contact with the circuit board.

For ceramic, mylar, and mica capacitors, press the leads straight into the circuit board holes. Note: Leave about a 1/8″ space between the capacitor and the circuit board. The reason for this is to keep any of the insulating material on the leads away from the soldering connection. This could make it difficult to solder the leads to the foil. Refer to Fig.7.

Diodes

Diodes are a two element device made of germanium or silicon that allow conduction or electric current much easier in one direction than the other. They are used as switching devices and rectifiers.

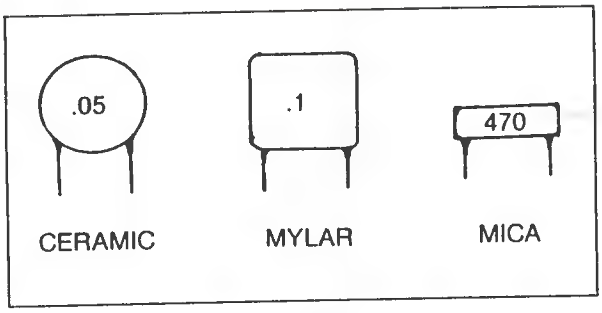

Fig.7: Ceramic, mylar, and mica capacitors

The schematic symbol for diodes is shown in Fig.8.

Installation

Since diodes conduct in one direction, it is

2.3 Component handling

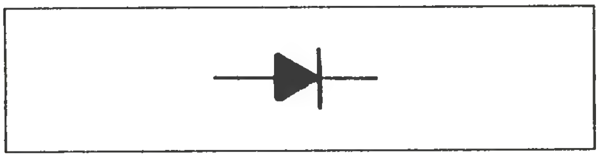

Fig.8: Diode symbol

very important to install the diode in the proper direction of current flow. Be sure the positive side (bar) and the negative side (arrow) are in the correct position.

When installing a diode to a circuit board, bend the leads at 90 degree angles to the body of the diode. Insert the leads into the circuit board holes and press the diode down until the body touches the circuit board.

Transistors

Transistors are semiconductor devices having three or more electrodes, and capable of performing almost all the functions of vacuum tubes, including rectification and amplification. Germanium and silicon are the main materials used, with impurities added to make up the conductivity type (n-type has an excess of free electrons; p-type a deficiency). Conduction is by means of electrons (elementary particles having the smallest negative electrical charge that can exist) and holes (mobile electron vacancies equivalent to a positive charge).

The schematic symbols for transistors are shown in Fig.9.

The three transistor leads – emitter, base, and collector – are shown in Fig.9.

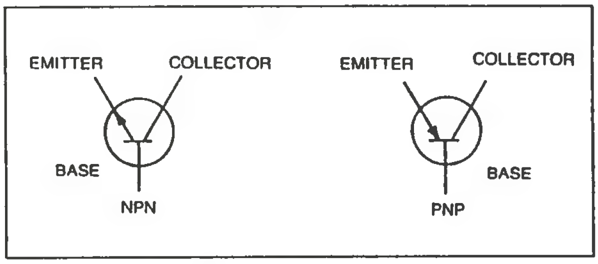

Fig.9: Transistor symbols

Installation

Care must be used when identifying the leads. Consult the specification of the particular transistor, because the lead configurations differ widely.

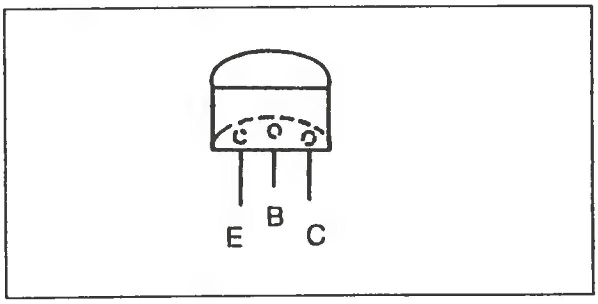

Fig.10: Transistor configuration, common

Before installing a transistor, bend the centre lead back slightly (away from the flat side). Insert the transistor leads into the respective holes in the circuit board. Leave a 1/4" space between the circuit board and the transistor.

It is impossible to list all the types of transistors on the market today. Lead configurations vary with the transistor

type and the manufacturer. Take time to identify the leads. Sometimes they are printed on the transistor. When soldering, you may want to use a heat sink on the leads if excessive heat is going to be used on the solder connection.

Integrated circuits

Integrated circuit is abbreviated IC. ICs are a combination of interconnected circuit elements located inside a common case. Access to the various circuits inside the case are made from metal pins. The IC is installed in a socket which has been soldered into the circuit. This makes replacing the IC a matter of pulling out the IC from its socket and inserting another one. However, in SMT (surface mounted technology) ICs are soldered directly to the circuit board, eliminating the socket. One advantage of this method is to get more ICs on the circuit board making the circuits more compact. The disadvantage is replacing ICs is much more difficult.

Installation

ICs all too often are put in their socket backwards. This will cause a malfunction of the circuit. Every IC has a locator to show where pin one is located. Sometimes the locator is an actual notch in the IC, and sometimes it is a circle located on top of the IC at the end near pin one. The IC socket will have a notch in the end where pin one is located. Pin one is always to the left of the locator. Refer to Fig.11 for locating identification.

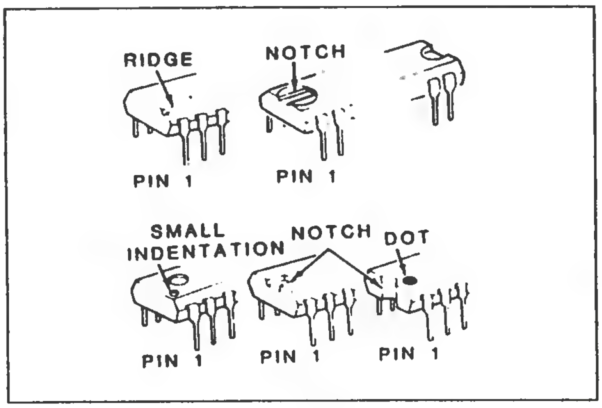

Fig.11: IC locator

When installing an IC, you will find that the pins tend to be spread wider than the IC socket. To make the IC fit the socket, grasp the IC from the top and roll it on the pins from side to side applying minimum pressure, the pins will be bent in just a little. Rolling the pins assures that all of the pins are bent in about the same amount. Refer to Fig.12.

Set the IC on the socket. Be sure that pin one and the locator line up with the notch in the socket. Gently rock the IC into the socket. Do not force it as one or more of the pins will bend under and not make connection. Firmly seat the IC in its socket.

Special IC tools are used to remove the IC from its socket. It is similar to tweezers with the ends bent in. The tool is placed over the IC so each leg of the tweezer catches in the ends of the IC. Then, pull up to remove the IC. You can also use a small non-magnetic screwdriver and, by alternately placing it under each end and prying up on the IC, it will come out of the socket.

2.3 Component handling

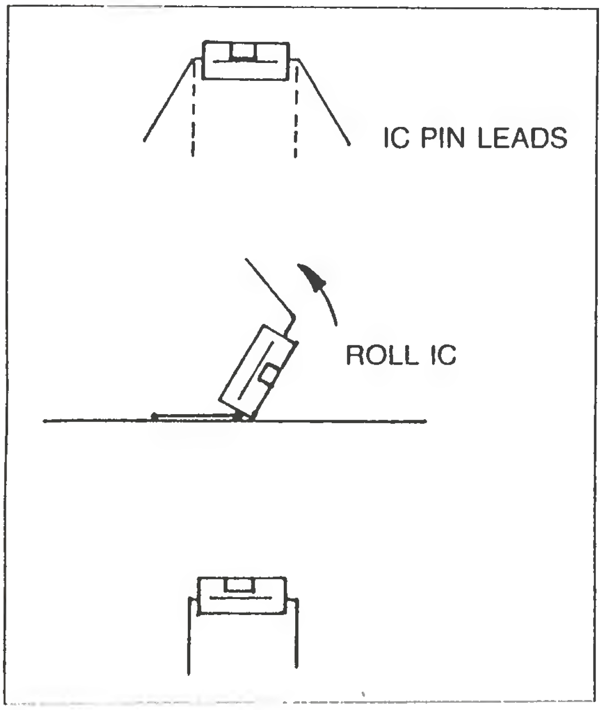

Fig.12: IC pin alignment

C-MOS devices

C-MOS devices are Complementary Metal Oxide Semiconductors. They are very durable and reliable components once they are installed in their socket. However, they are extremely sensitive to static electricity. The slightest amount of static electricity to the IC when it is outside the circuit can destroy it. Other types of ICs are not as susceptible to static electricity. But, it is good practice to treat all ICs as if they were C-MOS devices. Several precautions MUST be taken. First, the manufacturer ships the IC in a special anti-static foam. It is important when working with this type of IC that the IC remains in the foam until the time you are going to install it. Then, and only then can you remove it! DO NOT lay the IC down or let go of it until it is installed in its socket.

Your body is also an excellent source of static electricity. Before touching the IC, you should ground yourself. If you are working on a chassis, place one hand on the chassis and keep it there until the IC is in the socket. With the other hand, take the IC out of the protective foam and place it into its socket.

Summary

Electronic components come in a variety of sizes and shapes and they provide a wide variety of functions. It is important that they be properly identified for value, polarity, and pin location. Installing each component should be done with care, and it is best to be consistent when installing components. By that we mean always set the resistors in the circuit board so the banded sides are always on the left or the right. Be sure that when installing components with values marked on their side that those values are facing up so they can be read. Some components should be installed so they are against the circuit board while others are installed so they are set off the board about 1/8".

When installing transistors, be sure the emitter, base, and collector are put in the correct holes in the circuit board. Diodes allow current flow in one direction. If the diode is put in backwards, the circuit will malfunction.

When installing ICs, be sure to match up the locator with the notch in the socket. And when working with static sensitive devices, be sure to use as much caution as possible. Always ground yourself before handling the components.

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15

PRINTED CIRCUIT BOARD SOLDERING

LEARNING OBJECTIVES Upon completion of this chapter on printed circuit board soldering, the student should be able to:

1. Understand the composition and temperature characteristics of soft solder.
2. Know the major classifications of fluxes and their applications.
3. Know the available soldering iron tip configurations and their temperature requirements for a variety of soldering applications.
4. Use a soldering iron to solder pc board connections.
5. Be familiar with common solder joint deficiencies, their causes, and methods to correct them.
6. Use de-soldering aids and tools.
7. Properly dip solder pc boards.
8. Understand the wave-soldering process and the basic components of a wave-soldering system.

15.0 INTRODUCTION

With the components properly assembled, the final process necessary to complete the construction of the pc board is to produce sound electrical connections between the leads and the foil pattern. These connections can be produced by several methods, the most common of which are *welding* and *soft soldering*. Welding

requires the use of complex and expensive equipment and, as such, is rarely used in fabricating a prototype pc board. Soldering, on the other hand, can be performed quickly with less expensive equipment and results in excellent mechanical and electrical connections and protects the joint from oxidation. For these reasons, soldering will be discussed exclusively in this chapter.

Soldering is a metal solvent or chemical alloying action of the solder with the surfaces of the metal parts between which an electrical connection is formed. This completely metallic contact is produced by the application of soft solder with the heat of a soldering iron to the joint between the component lead and the terminal pad. The resulting connection is electrically sound, with the new alloy formed having different electrical and mechanical characteristics than either the solder or the metals joined. The soldering of pc boards requires the development of proper techniques if quality results are to be obtained.

The three methods of soldering discussed in this chapter are (1) *hand*, (2) *dip*, and (3) *wave* soldering. These three methods are used extensively in pc board applications.

Specific information is also provided on the following topics: soft solder and its characteristics; the types of *flux* available and its application; the soldering iron, including the *tip*, *power rating*, and *tinning* processes; and hand-soldering techniques, with emphasis on the proper soldering of leads, swaged terminals, and conductor paths (tinning). A discussion of the characteristics of correct solder connections is presented to aid in visual inspection. *De-soldering* and the solvents used to remove the flux residues formed on soldered connections are also included. Finally, information on production-line methods of soldering, specifically dip and wave soldering, is presented.

15.1 SOFT SOLDER AND ITS CHARACTERISTICS

Soft solder used extensively in electronic equipment construction is an alloy principally of *tin* and *lead*. Soft solder is differentiated from hard solder by its tin content and lower melting point. The amount of tin contained in soft solder ranges from 50 to 70%. The tin–lead ratio determines the strength, hardness, and melting point of the solder.

Solder liquefies at temperatures between 361 and 621°F (183 to 327°C), the exact temperature depending on the tin–lead ratio. A metal such as copper, which has a melting point of 1981°F (1083°C), can be successfully alloyed with solder at temperatures well below this value because of the *solvent action* of solder when it is liquefied. At the melting point of solder, a thin film of metal is dissolved from the copper surface, forming an alloy and establishing an electrically continuous joint. The formation of this alloy between the metal and the solder has its unique physical properties, such as torsional, shear, and tensile strength, which are different from those of either the solder or the metal. These properties will vary widely and will depend on the depth of alloying into the metal surface.

Pure tin melts at 450°F (232°C) (point *B*, Fig. 15.1) and the melting point of pure lead is 621°F (327°C) (point *A*). When these two elements are combined, the melting point of the solder formed can be below that of either pure metal. A

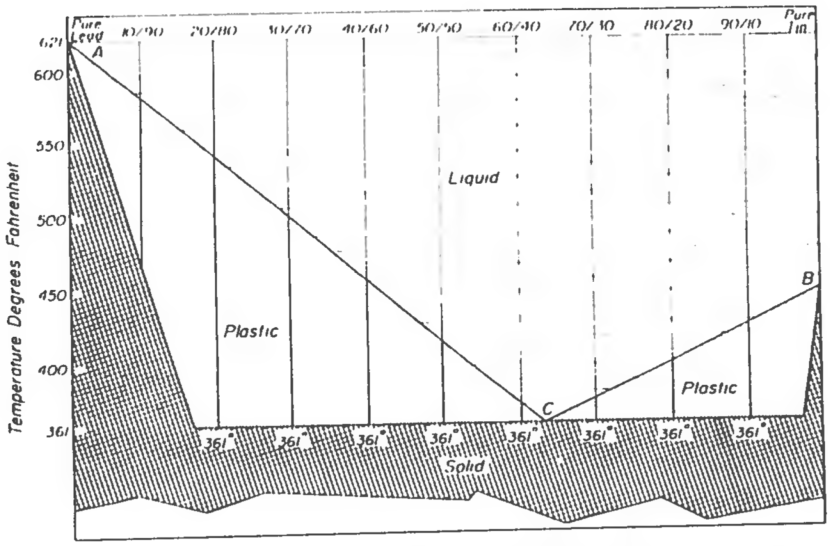


FIGURE 15.1. Tin–lead fusion diagram. *Courtesy of Kester Solder, Division of Litton Systems, Inc.*

composition of 63% tin and 37% lead melts at 361°F (183°C), which represents the lowest melting point and most rapid transition from the solid to the liquid state of any other tin–lead ratio. This point, *C*, is also shown in Fig. 15.1. The 63/37 solder is termed the *eutectic* composition. All solder, with the exception of the eutectic composition, which melts sharply from solid to liquid, passes through a stage of softening between its solid and liquid stages known as the *plastic range*. A fusion diagram showing the temperature ranges for the various states of solder for all tin–lead combinations is shown in Fig. 15.1.

In order to determine the proper tin–lead ratio for a specific application, the function of the connection must be examined. The necessary properties that will dictate the composition of solder are mechanical resistance to fractures due to stress, ability to form a continuous metallic connection at low temperatures, and cost. These factors are discussed here.

Since tin is more expensive than lead, solder with a higher tin content is more costly. It has been shown empirically that the highest joint resistance to stress exists with a 63/37 tin–lead ratio (eutectic solder). This concentration, therefore, affords the best alloying qualities in addition to the lowest melting point.

For most hand-wiring and printed circuit applications, solder with a tin–lead ratio of 60/40 is commonly used, because of its excellent wetting action. *Wetting* is the term used to describe the ability of the solder to readily spread and alloy uniformly over the entire metal surfaces to be joined. Eutectic solder is sometimes selected to take advantage of the lowest and sharpest melting-point characteristics wherein maximum precautions are necessary to avoid component heat damage and upsetting the joint as it cools. If these two considerations are not critical, 60/40 solder is an excellent compromise.

Solder for electronic applications is available in bars, sheets, wire spools, and special forms, such as pellets, rings, and washers. For hand-wiring purposes, solder wire ranges from 0.030 to 0.090 inch in diameter. The larger sizes are used for general-purpose work and the smaller for delicate soldering applications such as pc boards and solder pot-type pins (see Chapter 23) found on certain connectors.

Solder wire is also available with a core containing flux (see Sec. 15.2) in specific amounts to promote sound solder connections. For this reason, flux-core solder wire is used almost exclusively for electronic applications.

15.2 FLUX

The interaction of metal parts with the atmosphere forms a thin layer of oxide on their surfaces. This oxidation increases as the metal is heated and will severely interfere with the solvent action of solder, thus preventing alloying and the formation of an electrically continuous joint. Consequently, the oxide must be removed. *Fluxes* are used for this purpose. They are chemical agents that aid in soldering by removing thin films of oxide present on the metal surfaces to be soldered. When applied to the joint, the flux attacks the oxides and suspends them in solution, where they float to the surface during the soldering process. When the joint is heated, the presence of flux also prevents further oxidation in addition to lowering the surface tension of the metals, thereby increasing the wetting action. It is important to remember that flux is not a cleaning agent for removing grease or other contaminants. Its sole function is to remove the oxide film. For optimum soldering results, the parts must be thoroughly cleaned before the flux is applied.

The flux in no way becomes a part of the soldered connection but aids in the process. Upon completion of the soldered joint, a flux residue appears on its surface, which contains the captured oxides. This residue should be removed with an appropriate solvent.

The ability to rapidly remove oxide films from metal surfaces constitutes *activity* of the flux. It would appear that a highly active flux is ideally suited for electronic construction since it would afford rapid alloying and thereby reduce the possibility of heat damage to the components. This, however, is not the case. Highly active fluxes may be corrosive at room temperature and, if allowed to remain as a residue, will deteriorate the conductor surfaces or reduce the resistance of the insulation between soldered connections. Corrosive damage to components may also occur, since some of the active residues will gradually spread as they absorb moisture from the atmosphere. Even with suitable solvents, there is no assurance of complete flux residue removal, especially around closely spaced terminals, connectors, or conductors on pc boards where complete solvent flushing is not possible.

There are three major classifications of flux: (1) *chloride* (inorganic salts), (2) *organic* (acids and bases), and (3) *rosin* fluxes. The chloride types are the most active (highly corrosive) fluxes. They absorb moisture from the atmosphere and strongly react with acid even at room temperature. Organic fluxes are slightly

less active than the chlorides and are used mainly for confined areas in which fast soldering time is important and corrosion problems are not critical. Many of the organic fluxes are converted to an inert residue after thermal decomposition. They do not absorb moisture and are difficult to remove. For the reasons given above, chloride- and organic-type fluxes are not recommended for use in electronic construction. The rosin-type fluxes are used almost exclusively because of their noncorrosive characteristics at room temperature. They are corrosive at temperatures near the melting point of solder. Consequently, they attack the oxide film during the heating cycle but are inactive when room temperature recurs. Rosin fluxes are available with activating agents that greatly improve their activity. These activated rosin fluxes are much more corrosive than pure rosin when heated and present the appearance of an instantaneous melting, wetting, and flowing action of the solder. They are essentially as noncorrosive at room temperature as the pure rosin types and are often preferable if a higher degree of flux activity is dictated such as in dip or wave soldering.

Liquid flux may be applied by *wiping*, *dipping*, *spraying*, or *sponging*. Wiping or dipping methods are not extensively used. Uniform flux coatings are difficult to realize when wiping with a brush and thorough wetting of all surfaces may not result when dipping because of air pockets or cavities created during this process. Another disadvantage of these two methods is that application of an excessive amount of flux requires extensive removal of residue after the soldering has been completed.

Spraying flux involves applying a fine mist to the joints. The use of this method ensures that leads and terminals are more uniformly and completely coated with flux. When spray methods of flux application are to be used, the manufacturer's literature should be consulted regarding the recommended spray gun, nozzle, pressure, and solvent to use.

The application of flux with a sponge is perhaps the most effective and least messy method. To apply the flux, the board is firmly pressed against a sponge that has been saturated with liquid flux.

When hand soldering, the proper amount of flux can best be applied with the use of *flux-core wire solder*. This form of solder contains a core of solid rosin flux in a single or multiple core. There is no significant advantage in using multiple-core solder since it is essentially the volume ratio (amount of flux to solder) that determines optimum soldering conditions. Core sizes are available that provide a ratio of rosin flux per unit volume of solder of 0.6 to 4.4%. These ratios can be obtained for any size of wire solder. Indications are that 60/40 rosin flux core solder with a diameter of 0.040 inch and 3.6% flux is ideally suited for hand soldering pc boards and other electronic precision work.

15.3 THE SOLDERING IRON

The soldering iron, shown in Fig. 15.2, consists of four basic parts. These are the (1) *tip*, (2) *heating element*, (3) *handle*, and (4) *power cord*. Some soldering irons are equipped with either a cork finger grip or a heat deflector. These are designed to improve thermal insulation in the handle, which tends to become hot afte

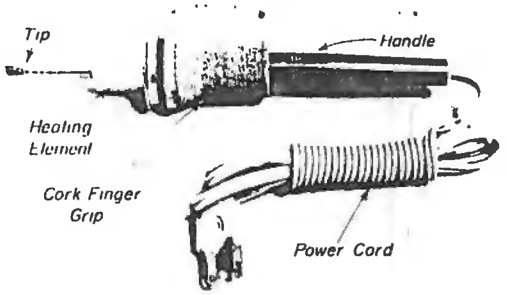


FIGURE 15.2. Soldering iron nomenclature.

prolonged use. In addition, the cork finger grip allows for more comfortable use of the iron.

When power is applied to the soldering iron, the tip is heated by direct thermal contact with the heating element into which it is set. The tip shown in Fig. 15.2 is an integral part of a porcelain-type heating element. The solder is liquefied when it comes in contact with a tip that has reached its operating temperature.

A soldering iron is selected for a specific application by considering the following factors: (1) size and style of the tip, (2) tip material, (3) required tip temperature, and (4) tip-temperature recovery time.

Selecting a tip style is somewhat a matter of personal preference. However, the shape of the particular tip used must provide the largest contact area to the specific connection for maximum heat transfer while minimizing the possibility of heat damage to surrounding leads or components. Some of the widely used tip styles are shown in Fig. 15.3. Each of the available tip configurations is designed for a specific soldering application. A brief description and application of each tip shown in Fig. 15.3 follows:

> *Chisel-* and *pyramid-*style tips are commonly used for hand wiring and general repair work. The large flats of these tips allow large areas to be heated rapidly. The *turned chisel* and *conical chisel tips* lend themselves very well to soldering in confined areas, such as hand soldering components to double-sided pc boards.
>
> *Bevel* designs are suitable for soldering terminal pad connections on single-sided pc boards if extreme conductor pad density does not exist. This style allows rapid heat transfer owing to the large tip surface area.
>
> *Conical* tips are preferable for soldering high-density wiring, eyelets, and small heat-sensitive parts.
>
> *Radius groove* tips also work well in high-density soldering applications and on round configurations such as pin connectors, pot-type terminals, and turret terminals.

Soldering iron tips are manufactured chiefly from copper and are available both in plated and unplated finishes. Typical platings for tips are *iron*, *gold*, and *silver*. These platings protect the copper tip from corrosion and pitting, which

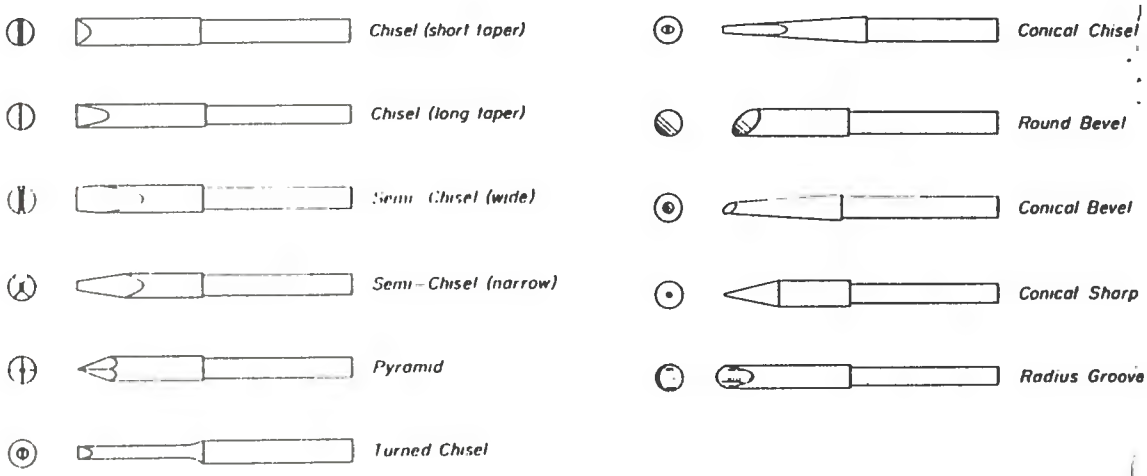


FIGURE 15.3. Solder tip configurations.

become pronounced over extensive periods of use. The plated tips should never be filed or cleaned with harsh abrasives that would remove the plating and expose the copper. The tips should instead be periodically cleaned by first dipping them cold into liquid rosin flux and then bringing them up to operating temperature to loosen any surface oxidation or contaminants (burned solder and flux residues) that may be present. Solder is then applied to the hot tip. Contaminated areas are easily detected by observing those areas that resist wetting by the solder. Sufficient solder has been applied when it begins to puddle. The tip is then wiped on a moist fine-pore cellulose sponge to remove the contaminants.

Tips should periodically be removed from the soldering iron because oxide will build up on the shank or threaded portion that fits into the heating element. If this oxide formation is not occasionally removed, the tip will seize in the element, making it difficult to remove and possibly damaging the element.

The required tip temperature is based on its application. For general-purpose soldering, such as to terminal strips and solder lugs, a tip temperature of 600 to 900°F (316 to 482°C) is sufficient. Printed circuit soldering requires fast heat transfer to the foil, yet excessive heat that could upset the foil bond must be avoided. For soldering to conductor patterns having widths of $\frac{1}{32}$-inch or larger and for terminal pads having $\frac{3}{32}$-inch diameters or larger, irons with tip temperatures of 800 to 850°F (427 to 454°C) are recommended. When soldering to more delicate pc boards or extremely fine wire (28 gauge or smaller), tip temperatures of 550 to 700°F (288 to 371°C) are suggested. However, when fine-component wire is to be soldered, especially in the case of heat-sensitive devices, a tip temperature of at least 900°F (482°C) is recommended (if lead heat sinks are not used) so that rapid heat transfer occurs with a minimum amount of tip contact time.

Manufacturers normally rate their irons in *watts*, typically available from 20 to 60 watts for electronic application. It is difficult to compare exact tip temperature with wattage rating since the length and the diameter of the tip largely influence tip temperature. For example, a 25-watt iron with a $\frac{3}{16}$-inch tip diameter

TABLE 15.1

Comparison of Wattage Rating and Tip Temperatures for Various Sizes of Solder Tips

Diameter (D) in Inches	*Length (L) in Inches*	*20W*	*25W*	*30W*	*35W*	*40W*	*50W*	*60W*
3/64	3/4	675°F	725°F	775°F	825°F	875°F	925°F	975°F
1/8	3/4	640°F	690°F	750°F	800°F	860°F	910°F	960°F
3/16	3/4	630°F	680°F	730°F	790°F	850°F	900°F	950°F

and $\frac{3}{4}$-inch tip length will produce a temperature of approximately 680°F (360°C). Another 25-watt iron with a tip having the same $\frac{3}{16}$-inch diameter but a $1\frac{1}{2}$-inch length will reach a temperature of approximately 605°F (318°C). As a rule, tip temperature decreases linearly, approximately 10°F for every 0.10-inch increase in tip length. Tip temperature is inversely related to tip diameter. However, this relationship is not linear, as is the case of length versus temperature. Therefore, empirical data, such as that provided in Table 15.1, must be consulted. This table shows comparative values of tip temperatures to specific wattage ratings for three common tip diameters. The values given in this table are for iron-clad chisel-style tips having a length of $\frac{3}{4}$ inch.

A more general relationship of wattage to tip temperature is given in Table 15.2. This table provides a comparison of the common wattage ratings to a range of tip temperatures that can be expected from any style or size tip. In general,

TABLE 15.2

Soldering Iron Wattage Rating vs. Range of Tip Temperatures

Wattage Rating	*Range of Tip Temperatures*
20 Watts*	550 to 750°F
25 Watts*	600 to 800°F
30 Watts*	650 to 850°F
35 Watts*	700 to 900°F
40 Watts	750 to 950°F
50 Watts	800 to 1000°F
60 Watts	850 to 1150°F

*Commonly selected wattage ratings for electronic applications.

approximately a 50°F change in tip temperature can be expected between th successive wattage ratings listed.

There is a useful technique for determining the approximate tip temperatur of iron-clad tips by visual inspection. When the iron is heated to its *idling* (max imum operating) temperature, the flats of the tip are alternately wiped severa times across the surface of a moist sponge. The color of the tip is observed 2 t 3 seconds after wiping. There is a relationship between the color obtained and th approximate tip temperature. This relationship is given in Table 15.3. Tip tem perature can be periodically monitored using this technique.

Recovery time is the rate at which a tip will return to its idling temperatur after transferring heat (tip cooling) to the work during soldering. In mass produc tion applications wherein a rapid succession of soldered connections are to b made, fast recovery time is absolutely essential. It is not of major concern i prototype work, however, since the recovery rate is normally much greater tha the rate at which soldered connections are made.

The following example will serve to illustrate how to evaluate the man available irons and tips to select the most appropriate one for a specific applicatio An iron will be selected for soldering a *double-sided pc board having typic conductor widths of $\frac{1}{32}$ inch with terminal pads of approximately $\frac{1}{16}$ inch in dian eter.* Ideal tip temperature for pc board soldering is 800 to 850°F (427 to 454°C As can be seen in Tables 15.1 and 15.2, a wattage rating of 35 watts will provi this necessary temperature with a $\frac{3}{64}$- by $\frac{3}{4}$-inch tip. The style of tip should perm ready access between components. A *conical chisel* design is selected since th configuration provides the desired contact area for component lead soldering terminal pads. Finally, the iron-clad finish is chosen for durability. The tip s lected for this example is quite versatile because of its thin chisel shape, whi works well with both double- and single-sided boards.

In general, the soldering iron that produces the best performance over a extended period of time is one that has high heat conductivity and low heat lo when in contact with connections to bring them up to soldering temperature. should also have a cool, lightweight handle, a no-burn power cord with stra

TABLE 15

Reference for Iron-clad Tip Temperature by Visual Inspecti

Tip Temperature	*Tip Color (2 to 3 seconds after sponge wipe)*
700°F	Silver
800°F	Gold
850°F	Gold with streaks of blue at tip
900°F	Blue to Purple
1000°F	Ash Black

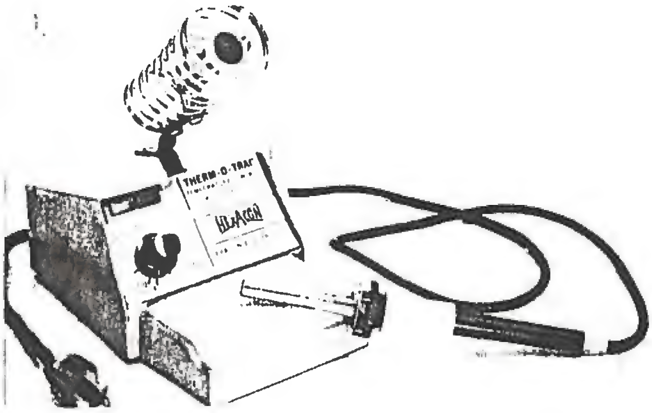


FIGURE 15.4. Temperature-controlled soldering iron. *Courtesy of Hexacon Electric Co.*

relief and a simple method for removing the tip and disassembling the iron to replace the heating element.

Where precise control of tip temperature is required, *temperature-controlled* soldering irons having tips with built-in temperature sensors are available. This type of iron is shown in Fig. 15.4. Temperature-controlled units allow for tip temperature settings from 500 to 800°F (260 to 427°C). They maintain the set idling temperature to within seconds after each soldering operation. This type of temperature control ensures consistent soldering temperature conditions.

15.4 HAND SOLDERING PRINTED CIRCUIT BOARDS

Of prime importance in soldering is that the surfaces to be joined are clean and void of oxides. For pc board soldering, this is especially true, for a poorly cleaned terminal area would prolong heating time excessively when soldering, which could upset the foil bond. The terminals should not only be cleaned but it is imperative that liquid flux be applied to all joints prior to soldering even if terminal areas have been tinned. The flux may be applied to the pc board by any of the methods discussed in Sec. 15.2. However, wiping is preferable in prototype work when a solder mask is to be employed, such as in the case of the amplifier's pc boards. This method allows the flux to be selectively applied only to those terminal areas that are to be soldered. The pc board is first secured in a *circuit board holder* and tilted to a horizontal position. Liquid flux is then applied with a fine artist's brush or toothpick onto the areas to be soldered. This arrangement is shown in Fig. 15.5 for applying flux to the power supply board. When all the surfaces to be soldered have been coated with flux, soldering may begin.

To solder leads to pc boards, it is important that heat and solder be applied quickly and accurately. A small amount of solder is initially applied to the flat of the soldering iron tip (solder bridge) to promote rapid heat transfer to the joint (Fig. 15.6a). The entire flat of the tip surface is then placed in contact with the terminal area and lead simultaneously. The more surface area of the tip contacting the terminal pad and lead, the more efficient the transfer of heat (Fig. 15.6b). The

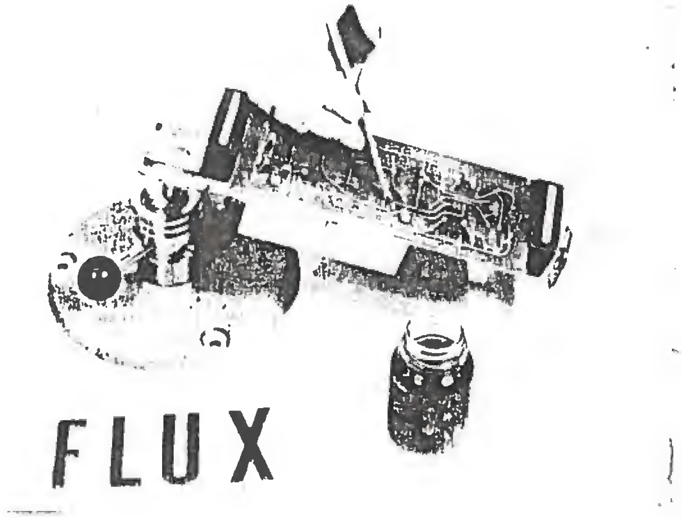
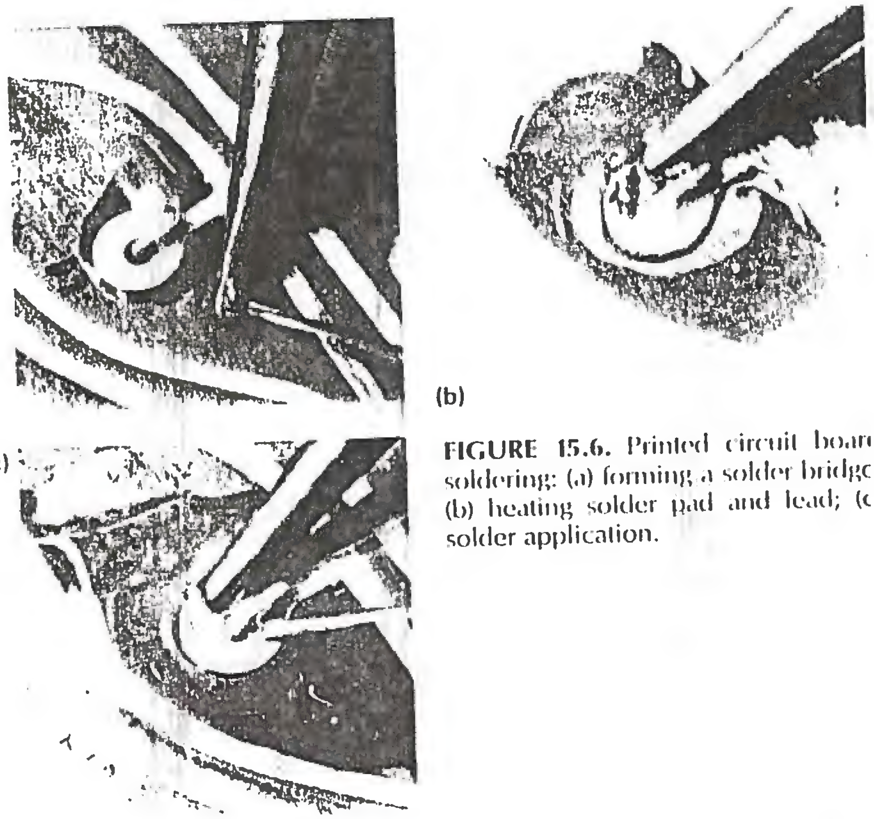


FIGURE 15.5. Application of liquid flux to selected areas.



(a) (b) (c)

FIGURE 15.6. Printed circuit board soldering: (a) forming a solder bridge; (b) heating solder pad and lead; (c) solder application.

joint is allowed to heat to the melting point of solder, usually taking from 1 to 2 seconds for most connections. Solder is then applied to the terminal pad and lead simultaneously and at a point on the opposite side of the lead from where the tip is contacting. The correct orientation of tip and solder is shown in Fig. 15.6c. As soon as the solder begins to flow, no more should be applied. Since solder follows heat flow, it will wet the entire connection and flow over the lead, forming a smooth contour of solder around the lead and terminal pad. The soldering iron is then removed and the joint allowed to cool. The joint must never be moved until the solder has completely solidified because any movement of the lead as it is cooling will prevent positive alloying from taking place. *It is important to apply only a minimum amount of solder sufficient to ensure proper alloying*. A properly formed solder joint is smooth and shiny in appearance. All surfaces must be completely wetted and the contour of the lead on the terminal pad clearly visible. A correctly soldered lead to a printed circuit terminal pad is shown in Fig. 15.7. A precaution should be mentioned here. When soldering the individual terminal pads, it is important to keep track of those leads that must be heat sinked. Lead heat sinking is discussed in Sec. 14.5.

Excess solder and contaminated flux residue on a tip must be removed before another solder joint is formed. Cleaning is accomplished quickly and easily by wiping the tip on a moist sponge. Soldering should never be attempted with a tip covered with excess solder or contaminants if quality results are to be expected.

Swaged terminals are soldered to pc boards in a similar manner to lead soldering, with one important exception. Since the terminal pad area for swaged terminals is larger than those used for lead connections, it is necessary to apply heat for a longer period of time. The flat area of the soldering tip is placed in contact with the swaged portion of the terminal and solder is applied to the terminal pad. When heated sufficiently the solder will completely wet the terminal pad and flow uniformly around the swaged terminal in the area where it contacts the copper foil.

Since many pc boards do not employ solder masks, and if conductor pattern plating is not economically feasible, the technican may wish to tin the entire conductor area of the board to retard oxidation. This can be done during the soldering operation. Flux is first applied to the entire board surface. A small amount of

FIGURE 15.7. Correctly soldered terminal.

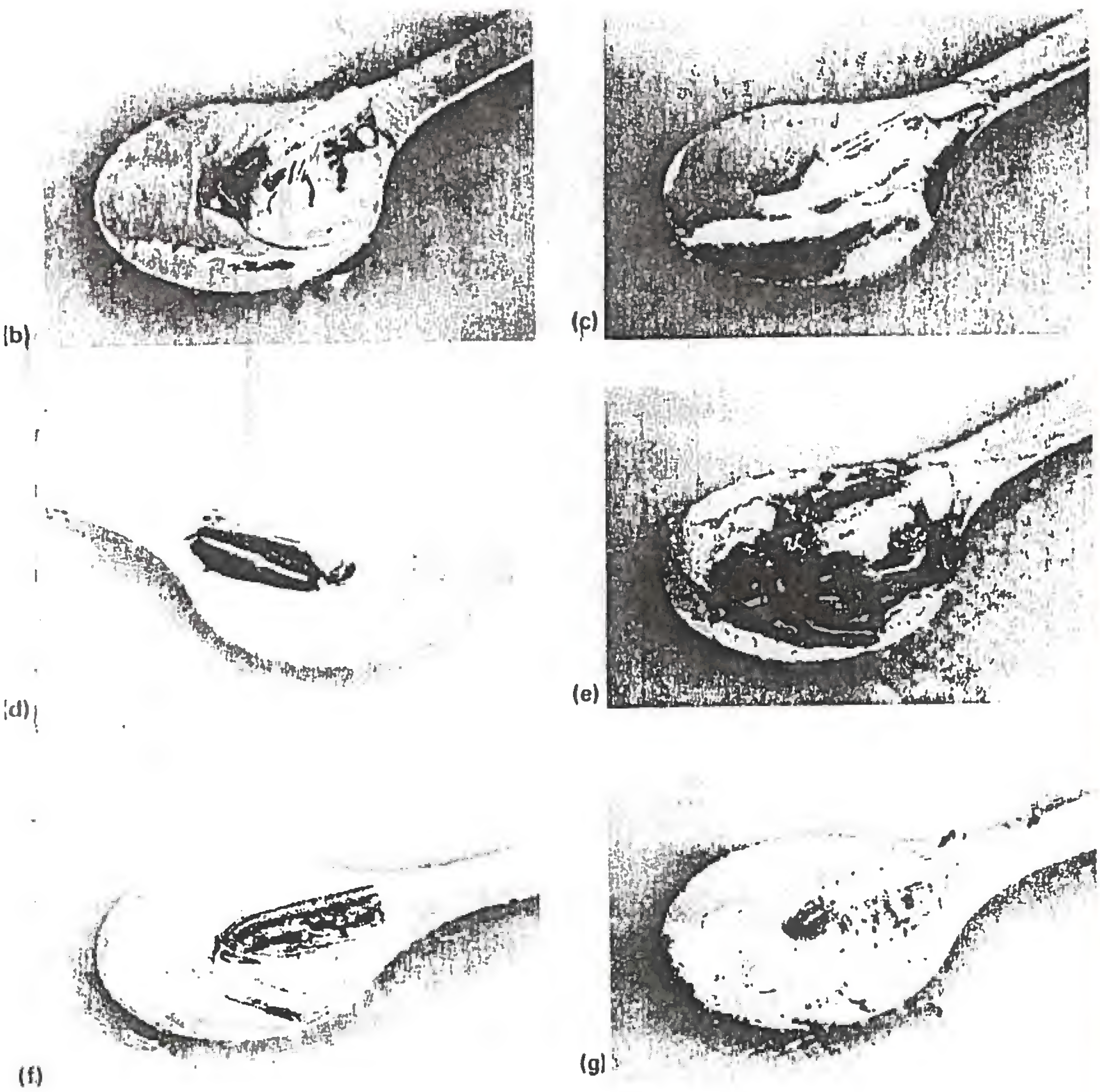
solder is applied to the flat of the tip and the tip is slowly drawn along the conductor path. A thin layer of solder will be deposited on the surface of the copper. Several passes may be necessary to completely tin a conductor path. This will prevent excessive solder from forming in addition to minimizing foil bond damage. For this technique, a soldering iron with a tip temperature of between 500 to 600°F (260 to 316°C) should be used. The application of solder via the soldering tip is restricted to tinning conductor patterns. This technique is never employed for making soldered connections.

Properly soldered connections are uniform in appearance and their quality may be judged by visual inspection. Each solder joint may be inspected immediately upon soldering or after completion of the entire board. To aid in this inspection, a 5× to 10× magnifying glass may be used. Following is a list of deficiencies and their causes common to improperly soldered connections. These are shown in Fig. 15.8.

1. *Solder peaking*—characterized by a sharp point of solder protruding from a connection. Peaking is caused by the rapid removal of heat before the entire joint has had an opportunity to completely reach its soldering temperature. The solder follows the hot tip as it is removed from the connection, resulting in this peaking condition. Reheating the joint will correct this deficiency.
2. *Incomplete wetting*—occurs when portions of the soldered connections have not been alloyed with solder and are completely visible. This may be the result of both insufficient heat and solder. It may also be the result of contaminants on the soldering tip or terminal pad. Reheating the joint and applying additional solder will correct this fault if the condition is not caused by contaminants. In that case, de-soldering and cleaning are necessary before a new joint is attempted. The terminal pad can be cleaned with a sharpened pencil-style typewriter eraser. (De-soldering techniques are discussed in Sec. 15.5.)
3. *Excessive solder*—evident when the lead contour is not plainly visible. This is extremely undesirable since it prevents complete inspection of the alloying action of the solder, thus obscuring potential troubles. This condition can be rectified by removing some of the solder with the use of de-soldering aids.
4. *Cold solder joint*—an inferior connection easily detected by its dull-gray, grainy appearance, or as a cluster of solder that has not properly wetted all the surfaces. This is the result of applying insufficient heat, which prevents solder from alloying with the metal parts. Cold solder joints can generally be corrected by reheating the connections. If, however, the puddling of solder is caused by a connection that has not been thoroughly cleaned, it must be de-soldered and cleaned before it can be properly soldered.
5. *Rosin joint*—a joint in which a layer of flux residue is formed between the terminal pad and the solder. Since flux is an insulator, this condition could

(a)

FIGURE 15.8. Typical inferior solder connections: (a) solder peaking; (b) incomplete wetting; (c) excessive solder; (d) cold solder joint; (e) rosin joint; (f) fractured joint; (g) porous joint.



result in electrical discontinuity between the lead and the terminal pad. Rosin joints are the result of too short a heating time. The soldering iron tip must remain on the connection for a short time after the applied solder is withdrawn. This allows proper wetting action and causes all the flux to float to the surface with the captured oxides. This defect can be corrected by reapplying heat.

6. *Fractured joint*—characterized by the appearance of minute cracks in the solder. These cracks appear if the lead is moved before the solder has had an opportunity to completely solidify. This may be corrected by the reapplying of heat, if the lead will not again be moved during the cooling period. This problem of component and lead movement arises when a pc board is soldered with the components resting on a work surface. It is preferable to clamp the board by its edges in a circuit board holder, such as that shown in Fig. 15.5.

7. *Porous joint*—characterized by pinhole imperfections visible in the surface of the solder which is due to trapped gases caused by insufficient heating time, a period required to allow volatizing flux to escape. This fault can be remedied by reheating.

Flux residue remaining on the connection after soldering is undesirable. This residue presents a poor board appearance and contaminants suspended in this residue could cause troublesome electrical leakage paths. If more active fluxes must be used, their removal is doubly important to prevent corrosion. Flux removal can be accomplished by *hand brushing*, *dipping*, or with *ultrasonic equipment*.

Brushing with a stiff-bristle brush dipped in a flux solvent is often acceptable but may not remove flux completely from inaccessible cavities characteristic of pc boards in which swaged eyelets and terminals are used.

Dipping and mildly agitating the board in a solvent bath is preferable since it will improve solvent action in some areas that are not possible to reach by hand brushing (Fig. 15.9).

A more efficient means of flux residue removal, especially when activated fluxes are used, is to use an ultrasonic tank containing the flux solvent. Several minutes in this system ensures the most thorough cleaning.

For most electronic soldering applications, rosin flux residue is the type most generally encountered. Alcohol and trichlorethylene are excellent solvents for this residue. As in the case of most solvents, certain hazards present themselves. Alcohol is flammable and trichlorethylene should be used in a well-ventilated area and kept away from the skin. Finally, the remaining solvents are quickly evaporated by the use of an oil- and moisture-free air hose.

The seven pc boards for the amplifier, hand-soldered and using the techniques discussed in this section, are shown complete and ready for assembly to the main chassis in Fig. 15.10.

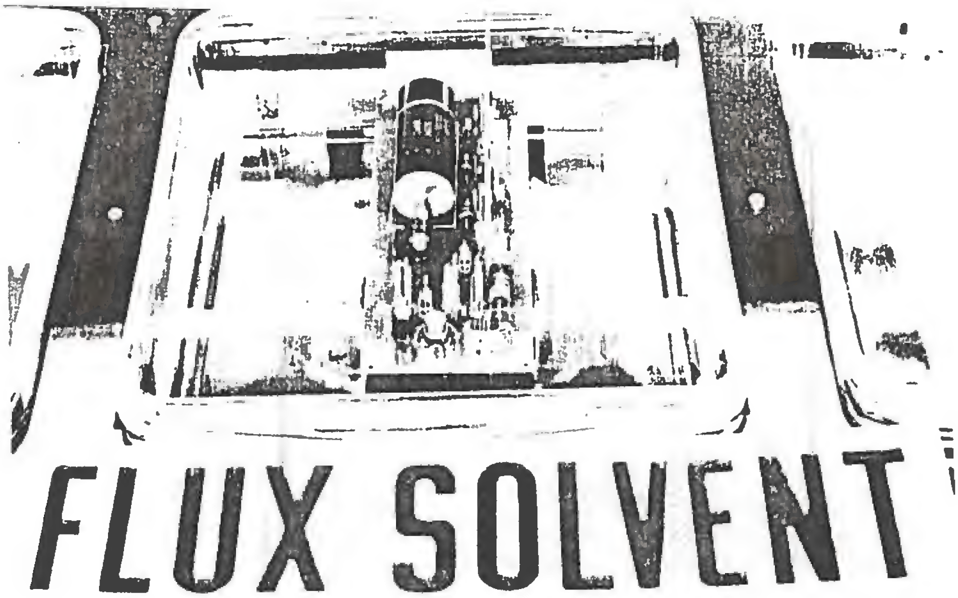


FIGURE 15.9. Mild agitation for flux removal is accomplished by use of a rocker table.

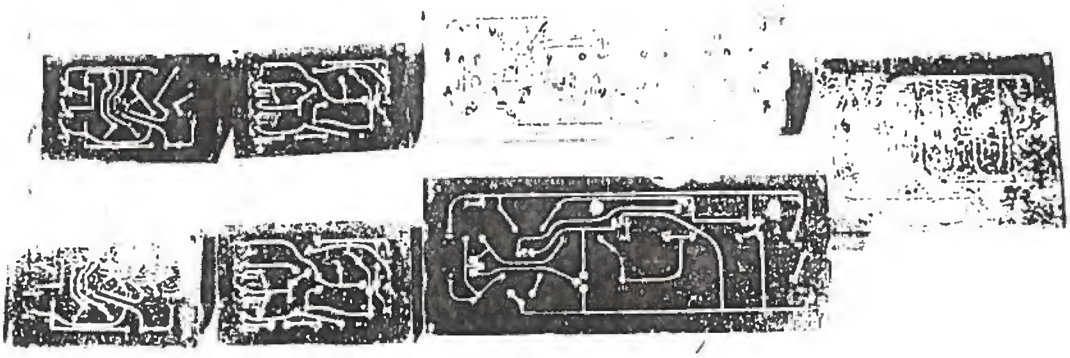
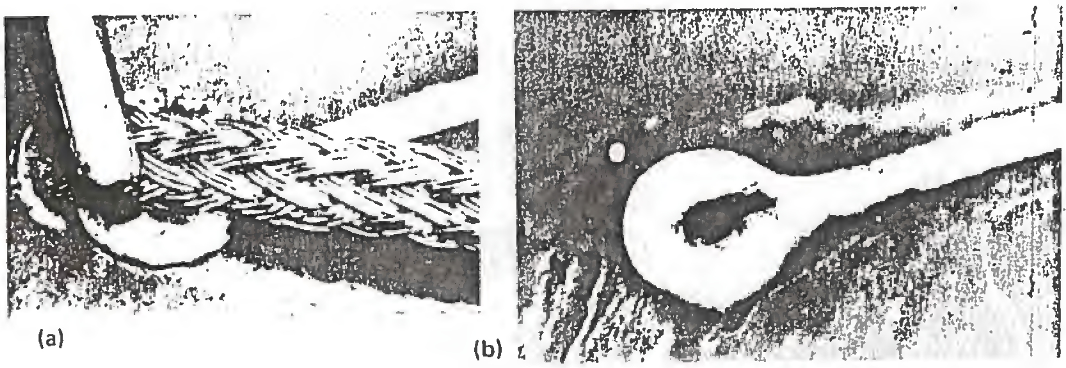


FIGURE 15.10. Hand-soldered amplifier boards.

15.5 DE-SOLDERING PRINTED CIRCUIT BOARDS

When a lead is soldered to a terminal pad, it is difficult to remove without damaging the component or the terminal area. Several commercially available de-soldering aids, however, simplify this task. These aids are the *solder wick, de-soldering bulb, solder sucker, de-soldering tips*, and *extraction tools*.

A solder wick is made of finely woven strands of tinned copper wire such as that used for shielding coaxial cable (see Chapter 23). This flattened wick is



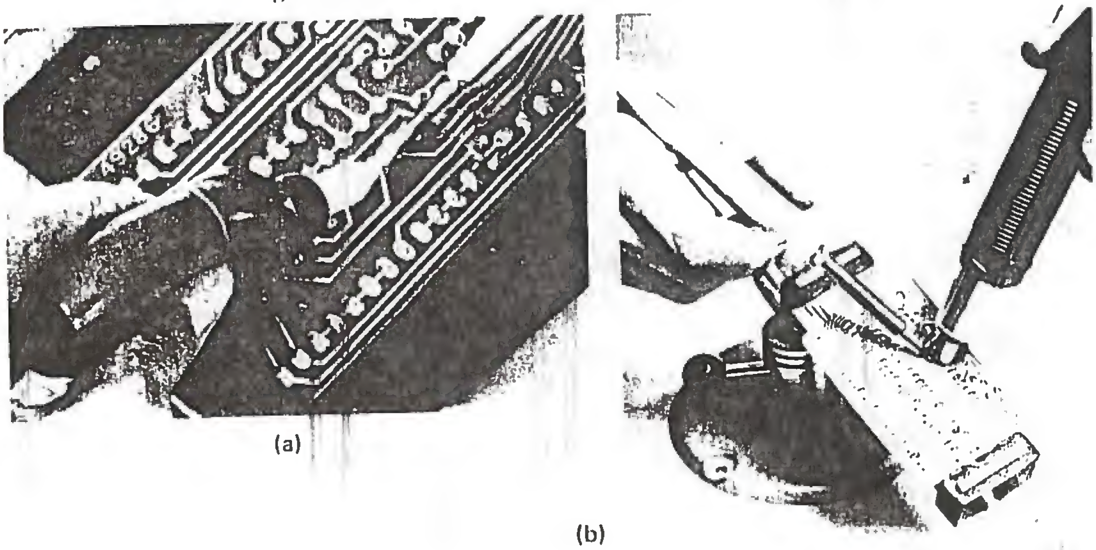
(a) (b)

FIGURE 15.11. De-soldering technique employing solder wick: (a) positioı of solder wick and soldering tip; (b) de-soldered terminal pad.

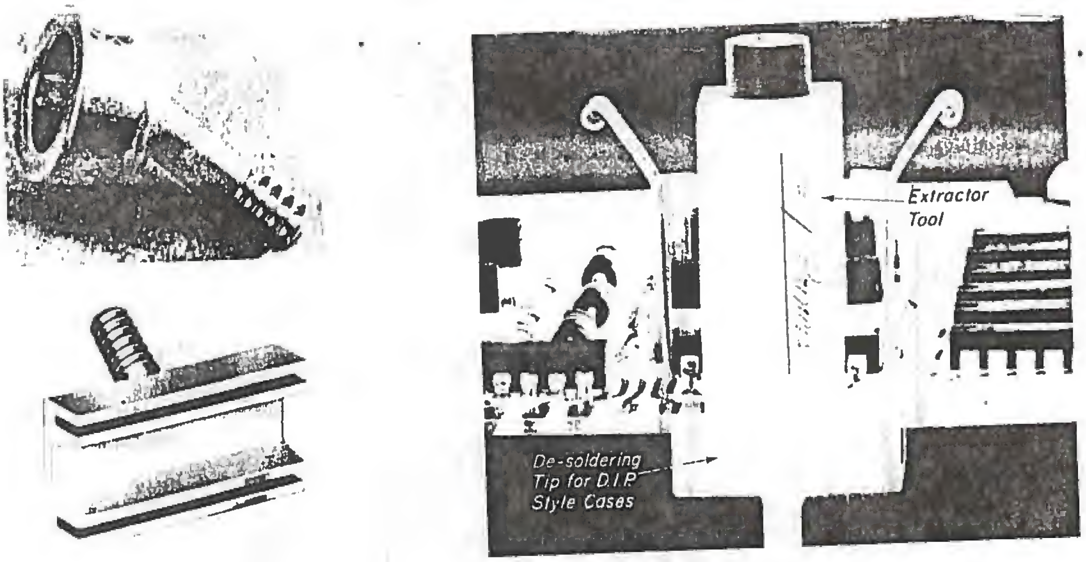
first dipped into a liquid flux to promote solderability. It is then placed over terminal area and lead to be de-soldered. This arrangement is shown in Fig. 15.1 The soldering iron tip is placed in contact with the solder wick and pressed dc against the connection. As the heat from the iron is transferred to the wick connection, the solder will melt and flow in the direction of the heat transfer. ' solder is thus trapped by the solder wick as it flows up through the weave. ' result is shown in Fig. 15.11b. The solder can be completely removed from joint with this method. The used portion of the wick is discarded. Solder wic available in rolls for many de-soldering applications. With the solder removed fı the connection, the lead can be bent away from the terminal pad and the com nent easily withdrawn.

The de-soldering bulb and solder sucker, shown in Fig. 15.12, can alsc used for removing excess solder or for de-soldering component leads. Both t

FIGURE 15.12. De-soldering equipment: (a) de-soldering bulb, *courtesy Ungar Division of Eldon Industries, Inc.*; (b) solder sucker.



(a) (b)



(a) (b)

FIGURE 15.13. Device de-soldering equipment: (a) de-soldering tips for T0-5- and DIP-style cases; (b) de-soldering DIP-style devices. *Courtesy of Ungar, Division of Eldon Industries, Inc.*

have hollow Teflon tips with high heat resistance and will not scratch or mar delicate pc board conductors. The de-soldering bulb, shown in Fig. 15.12a, is employed by depressing the bulb and then placing the hollow tip alongside the soldering iron tip on the joint. As the solder begins to melt, the bulb pressure is released. The liquid solder is drawn up into the bulb by the suction. Both tools are then removed from the connection for inspection. If solder remains, the process must be repeated. The solder-sucker shown in Fig. 15.12b is employed in basically the same manner except that the suction is produced by a spring-loaded piston. The piston handle is first pushed downward. The handle is then rotated to engage the release pin. As the solder begins to melt, the pin is disengaged and the solder is drawn up through the hollow tip as the piston snaps upward inside the tubular handle. Both tools are easily disassembled to remove the accumulated solder. These de-soldering tools do not generally remove sufficient solder on the first attempt to allow components to be removed, thus rendering the solder wick the preferable method.

For removing ICs, the previously discussed de-soldering aids would have to be used on each lead individually, making it a time-consuming process. De-soldering *tips* specifically designed to simultaneously heat all the leads for removing devices quickly and easily are available for this purpose. De-soldering iron tips for T0-5-style cases and dual-in-line configuration ICs are shown in Fig. 15.13.

The de-soldering tip is placed in contact with all the device leads simultaneously. As the leads are de-soldered from the foil side of the board, the device is removed from the component side with an extraction tool such as that shown

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in Fig. 15.13b. With this tool, the device is lifted away as the solder is melted. The remaining solder present on the terminal pad may obstruct the access holes and can be removed with any of the de-soldering aids discussed. The recom-mended type of extraction tool is one whose metal clamps grip the leads, thus providing some degree of heat sinking. It must also be mentioned that lead hea sinking is just as important when de-soldering as it is during soldering to avoic damage.

15.6 DIP SOLDERING

One method of soldering pc boards in mass production is *dip soldering*. Dip sol dering completely solders all connections and exposed copper conductors of th pc board in one operation. This process requires (1) *solder pot*, (2) *temperatur control unit*, (3) *bar solder*, (4) *dross removal tool*, (5) *board holder*, and (6) *flu applicator*. After the flux is applied to the conductor side, the board is floated o the surface of molten solder. An even coating of solder will be deposited onto th entire surface of the conductor pattern. Although this process appears basicall simple, the preparation and implementation are somewhat involved.

The preparation of the surfaces to be soldered is critical if quality result are to be realized. Absolute cleanliness is essential. The use of solder mask presents the fewest problems in dip soldering since the exposed areas to be sol dered are small and the possibility of *solder bridging* is eliminated. (Solder bridg ing is the undesired formation of solder *between* conductor paths.) Flux is applie to the surface just prior to soldering even if the conductor pattern has been tinnec

Flux may be applied, as previously mentioned, by either *dipping*, *wiping sponging*, or *spraying*. The object is to apply a uniform layer of flux over th entire surface of the board. This layer should be kept to a minimum thickness t promote improved solderability. If excessive flux is applied, it will not completel decompose at temperatures below those of molten solder, resulting in the forma tion of gas pockets between the board and the surface of the solder. These ga pockets will cause an uneven wetting of solder. Because of these limitations, wip ing with a brush is the most effective way of applying flux onto the board. Whe the flux has been applied, the board must be soldered immediately.

The specified tin-lead ratio for dip soldering is normally 60/40, which mel at approximately 370°F (188°C). Placing a pc board onto the surface of the mc ten solder will lower the solder's temperature. Consequently, a *guard temperatu* must be included to allow for this cooling. A guard temperature of between 5 and 70°F (10 to 21°C) is normally sufficient. This means that the solder pot ter perature should be maintained between 420 and 440°F (216 to 227°C) and a curately controlled. Although higher temperatures will hasten soldering, probler such as board warping and strain effects on the foil bond will be encountere The exact temperature for optimum results for any particular system is best d termined by trial and inspection.

As the solder pot is operated at elevated temperatures (above 370°F 188°C), an oxidizing scum, referred to as *dross*, will form on the surface of t molten solder. If not removed, this dross will adhere to the areas to be soldere

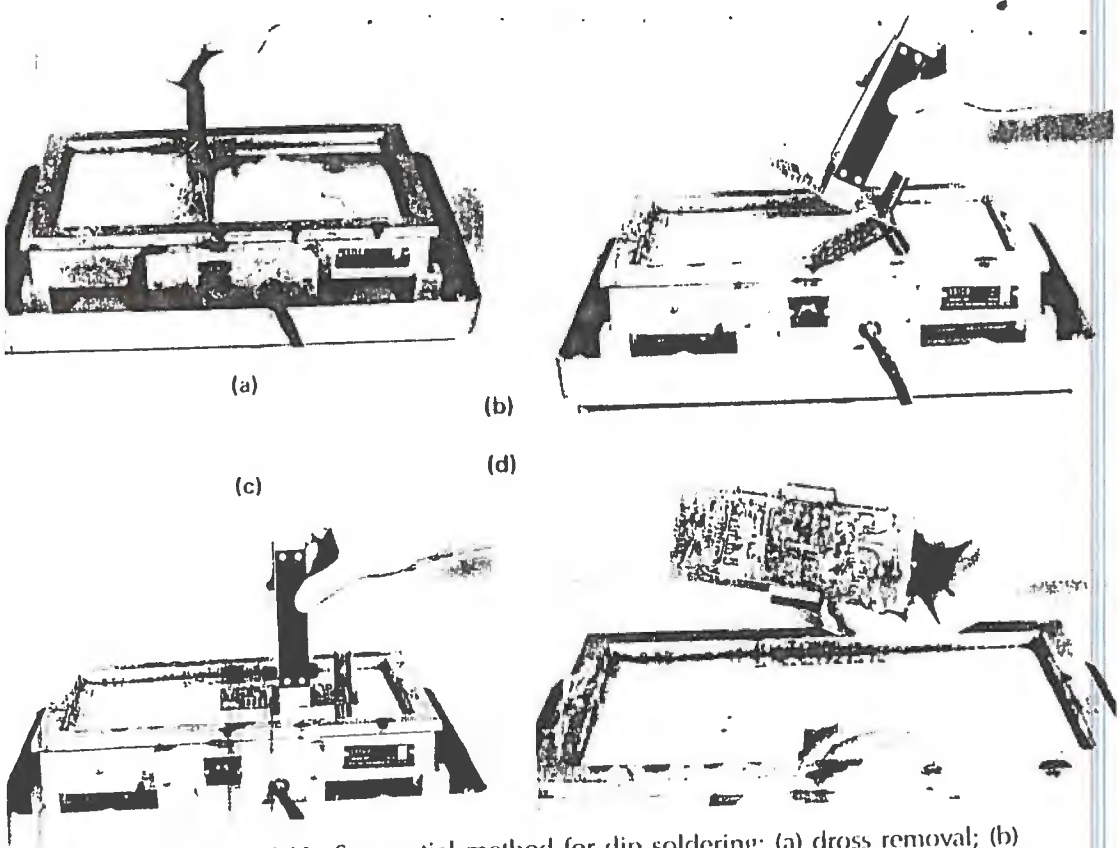

FIGURE 15.14. Sequential method for dip soldering: (a) dross removal; (b) initial board-entry angle; (c) board is moved about solder surface; (d) soldered conductor pattern.

resulting in cold solder joints. Just prior to floating the board onto the solder, the dross must be removed. This can be done by skimming the surface with a piece of aluminum mounted to an insulated handle (Fig. 15.14a).

The board is placed in the pot and held firmly along its edges with tongs equipped with insulated handles. First one end of the board is lowered in direct contact with the solder at an angle of approximately 45 degrees with the surface. This procedure is shown in Fig. 15.14b. The board is then slowly tilted downward until the entire conductor pattern surface is contacting the molten solder. This technique of slowly tilting the board will force any gases generated during the flux decomposition period to escape from between the solder and board surface. With the board in complete contact with the surface of the solder, it is moved about the pot (Fig. 15.14c) to allow uncontaminated solder to continually contact the conductor pattern. The soldering operation should take from 4 to 7 seconds, depending on the solder temperature and type and amount of flux used.

After the board has been allowed to remain in contact with the solder for the prescribed amount of time, it is slowly raised to a 45-degree angle before it is

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completely removed from the pot. This technique is intended to reduce the possibility of the formation of *solder peaks* (points of solder protruding from the conductor pattern). Visual inspection should be made to ensure that no solde bridges between closely spaced conductors have formed. Although solder canno alloy with the insulating material, bridges may still form between closely space conductors. The resulting appearance should be a completely wetted conducto surface with a smooth, uniform coating of solder. Once the flux residues are re moved, the board is completed. A properly soldered single-sided pc board is show in Fig. 15.14d.

Dip soldering, owing to its reasonable setup costs, can be adapted equall well to prototype applications. However, the results are not uniformly consiste or predictable. Often, hand-soldering touch-up work may be necessary to achiev quality results.

Extreme caution must be exercised when dip soldering. This process re quires continual safety precautions because of the ever-present danger inhere when working with molten metal. Protective glasses, gloves, and an apron shoul be worn to guard against solder splatter. Although a pronounced "sizzling" soun will be heard when the cool surface of the board first contacts the solder surfac this is normal and should not cause concern. This effect is the result of the rap volatilization of the flux. To prevent serious personal injury from a violent sold eruption, all liquids should be kept away from the solder pot.

15.7 WAVE SOLDERING

A much more elaborate system of production line pc board soldering that elin nates many of the inconsistencies resulting from manual dip soldering is the pr cess of *wave soldering*. This method is widely used in the industry because of large soldering capacity, its ability to accurately regulate time and temperatu exposure of the pc board, the scrubbing action of the solder wave which aids complete wetting and soldering of each joint area, and the consistently high-qu ity results obtained.

A typical wave-soldering system consists of three main sections. These a the *fluxer*, *preheater*, and *solder wave*. An integral part of the system is a convey which is used to accurately control the movement of the pc board over the flux the preheater, and the solder wave. Precleaning and post-cleaning cycles of the board are not a part of the system and are performed separately.

A typical bench-type wave-soldering machine is shown in Fig. 15.15. T conveyor speed is adjustable from 1 to 15 feet per minute at angles of betwee and 9 degrees with the surface of the bench. The board is introduced into system by attaching it to the fingers of the conveyor. The circuit side is first across a foam fluxer. At this station, a head of fine bubbles rise from the flu These bubbles are typically generated by passing air through a submerged por ceramic cylinder that is impervious to the flux. A chimney and brushes aid uniform flux distribution. The bursting flux bubbles rise by capillary action penetrate into plated-through holes. Rosin-based flux, such as Kenco No. Resin Flux, having 25% or higher rosin content, is generally preferred in

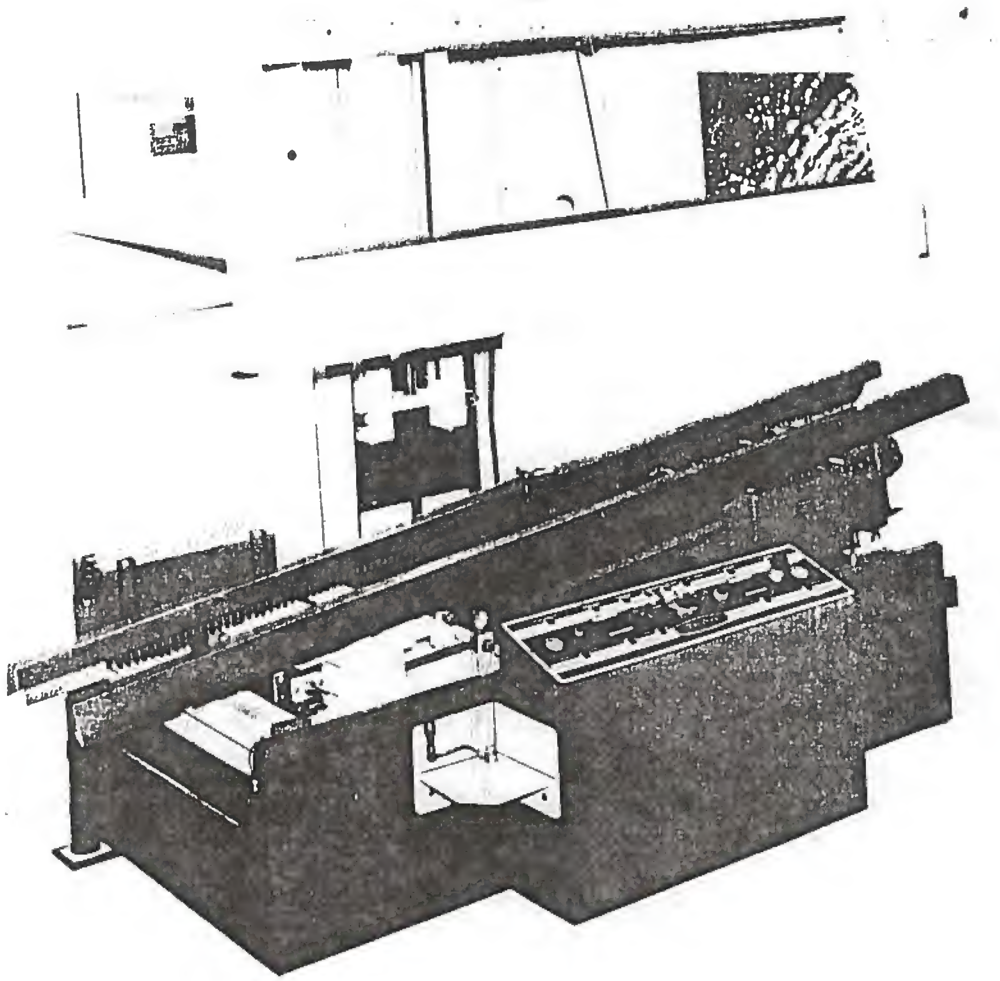

FIGURE 15.15 Bench-type wave-soldering machine. *Courtesy of the John Treiber Company.*

wave-soldering process. This flux not only promotes uniform solder wetting and formation of a strong intermetallic bond with the copper, but it also reduces the surface tension of the liquid solder. Surface tension reduction is important in preventing solder bridges and icicles (solder peaks) from forming.

After the board is fluxed, the conveyor continues its travel over a preheater station. The purpose of this station is threefold. First, preheating evaporates excess flux solvent on the board to prevent splattering and entrapped gases which could cause pinholes in connections when the board is soldered. Second, it conditions the board and assembly against thermal shock. Third, preheating the board helps to overcome the heat-sink effects on large components caused by the solder wave. Preheaters must be capable of providing a range of heat, as measured on the component side of the board, from 100 to 275°F (38 to 135°C). Overheating

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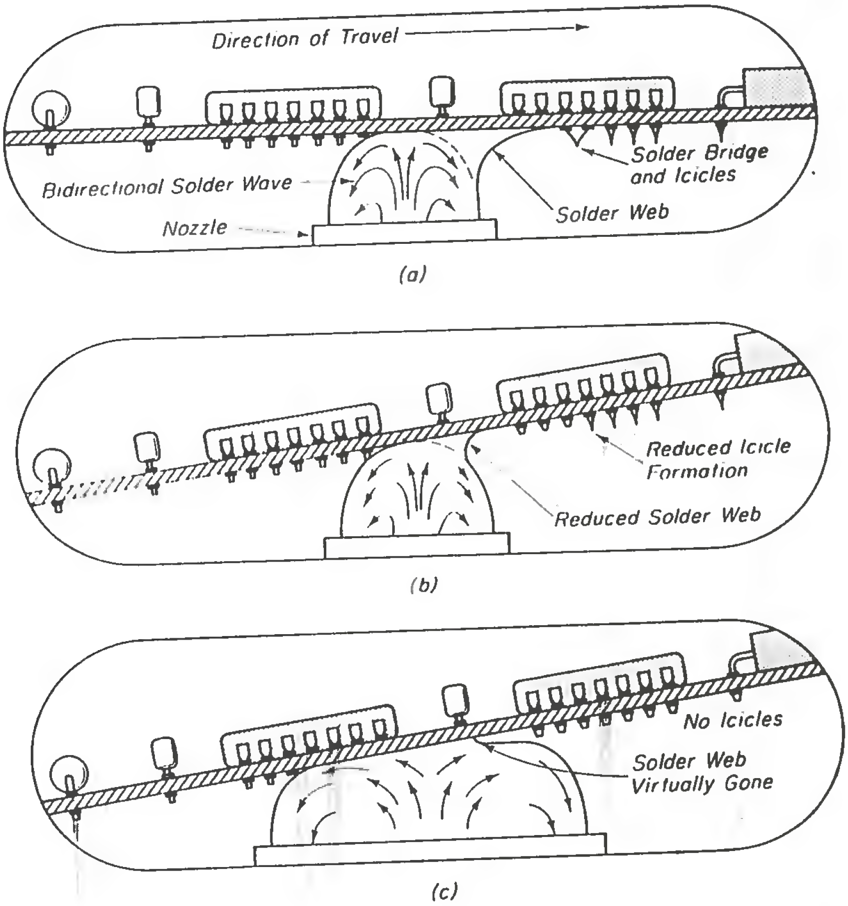
the flux must be avoided because it degrades its effectiveness by reducing its m
bility.

With the board preheated, it is next conveyed over the solder wave, wh
quickly produces large numbers of high-quality and well-contoured solder co
nections simultaneously. These connections are both electrically and mechanica
sound. The wave is formed by pumping molten eutectic solder (63/37) vertica
upward through a solder nozzle having a large plenum chamber that rests in
solder pot. A high-capacity centrifugal pump propels the molten solder throu
the nozzle to form a standing wave. The most commonly used wave shape
bidirectional, that is, solder flows in two directions.

Bridges and icicles will usually result if the solder system has too narrow
solder wave and the boards are run on a horizontal conveyor (see Fig. 15.16a)

FIGURE 15.16. Use of wide solder wave with oil and an inclined conveyor eliminates solder bridges and icicles: (a) narrow solder wave with horizontal conveyor; (b) narrow solder wave with inclined conveyor; (c) wide solder wave with inclined conveyor.



web of solder tends to extend beyond the wave in the direction of travel, which creates these problems. If the solder wave is narrow, inclining the conveyor to an angle of 5 to 9 degrees will increase solder *peel back* and therefore reduce the solder web and significantly reduce solder defects (see Fig. 15.16b). For best results, however, a solder system having a deep, wide wave (3 to 4 inches along the path of travel at 1 or more inches above the nozzle edges) and an inclined conveyor will virtually eliminate the formation of a solder web which cause bridging and icicles. This is shown in Fig. 15.16c. Inclining the conveyor causes the board to be introduced onto the solder wave at a high solder-velocity point. This takes advantage of the natural scrubbing action of the wave at this point in its velocity profile. A wider wave used together with an inclined conveyor also allows the soldered conductor pattern to exit the wave at a practically zero velocity point which not only increases solder *peel back* but reduces heat transfer to the components being soldered.

To obtain the smoothest solder wave and result in minimum solder deposits having a bright, shiny appearance, the formation of dross (oxides of tin and lead) must be kept to an absolute minimum. One method of reducing the dross formation is to use an oil (soldering fluid) as a dross blanket in the solder pot. As solder is pumped, the oil forms a thin film on the surface of the wave. Another effective method is to intermix oil, such as Hollis No. 225 Soldering Fluid, by precision metering with the wave at the impeller of the pump. This causes the oil to disperse uniformly within the solder wave. In both methods, the oil reacts with the dross to form harmless tin and lead soaps without degrading the solder. In addition, the surface tension of the solder is reduced which allows excess solder to drain more easily from the board. The soldered boards also become coated with the oil, which intermixes with the rosin flux and protects the soldered connections from oxidation. This mixture of oil and rosin is easier to remove than rosin alone in the cleaning process, assuring bright soldered joints.

Although wave soldering is an automated process, a degree of skill and knowledge of soldering is necessary to properly operate the system. This knowledge includes an understanding of the proper conveyor speed, type of flux, preheater temperature, width of the solder wave, solder temperature, the use of an oil blanket or oil intermix, and the established quality standards.

When the pc boards have been assembled, soldered, and cleaned, they may be tested for operational performance and modifications made if necessary.

EXERCISES

15.1 Lay out, shear, and bend an aluminum tray for holding a soldering iron tip cleaning sponge. The tray is to have inside dimensions of $\frac{3}{4}$ inch by $3\frac{1}{2}$ inches by $3\frac{1}{2}$ inches. Tabs are not required on the inside corners. These corners are sealed in Exercise 22.3 to retain excess moisture. Break all sharp edges with the appropriate file.

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QUALITY ASSURANCE INSPECTION PROCEDURES FOR PRINTED CIRCUIT BOARDS

LEARNING OBJECTIVES Upon completion of this chapter on techniques of quality assurance procedures for printed circuit boards, the student should be able to:

1. Understand the difference between destructive and nondestructive testing.
2. Use an inspection magnifier lamp to visually inspect a pc board.
3. Repair breaks in conductor paths.
4. Repair bridges between pattern features.
5. Use a comparator to measure pattern features.
6. Visually recognize hole-plating defects.
7. Use precision instruments to measure pc boards.
8. Use an ohmmeter to perform basic electrical testing.
9. Be acquainted with automated test equipment.
10. Microsection, inspect, and evaluate specimens from a pc board using a high-powered microscope.
11. Use a microscope to take precision measurements.

21.0 INTRODUCTION

The manufacture of a printed circuit board, whether it be a single-sided, double-sided, or multilayer design, requires many sequential processing steps, expensive equipment, and a considerable amount of materials and chemicals. Because of the

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numerous processes, some of them being quite critical, a finished pc board is prone to a host of faults. Problems such as defective materials, incorrect processing sequence, errors in chemical timing or temperature, and poor workmanship are not uncommon and never completely unavoidable. A fabricated pc board represents a significant cost to the manufacturer. Many detected defects are either correctable or acceptable and may not render a board useless. In addition, the components that are to be installed onto the board represent further major costs. For this reason, it is not economically sound to load a board that has not been inspected and tested to determine its acceptability. In this chapter we establish inspection procedures which will determine the quality of a processed board before the component assembly and final soldering processes are initiated.

It is not the intent of this chapter to define the absolute criteria for accepting or rejecting a processed pc board. These criteria are determined by the manufacturer of the product which is based upon the system's functionability and the standards of acceptability as defined by the pc board industry. The objective of this chapter is to identify the common features of a processed board to be inspected and to show the most appropriate method of determining the relative quality of these features. In many cases, a common problem is in interpreting the results obtained in the inspection procedure.

In general, inspection procedures for pc boards can be separated into two major categories: (1) *nondestructive* testing and (2) *destructive* testing. As the terms imply, the nondestructive test performed will not damage the board which is functional after inspection. This is the most cost-effective method of board testing. However, to accurately determine the quality of manufacture, a destructive test is necessary.

Nondestructive tests presented in this chapter are (1) *visual*, (2) *mechanical*, and (3) *electrical*. Visual inspections are those which can be made with the naked eye or with the aid of a magnification device. Mechanical inspection primarily involves the checking of measurements of length, width, thickness, and hole diameters. Electrical inspections can involve such tests as checking for short or open circuits on conductor patterns or within the inner layers of multilayer boards. Some of these tests use sophisticated computer systems that completely check the electrical pattern for any defects.

To properly test a pc board, all three methods, visual, mechanical and electrical, should be employed.

The treatment of destructive testing will include the preparation and interpretation of microsectioned samples of plated-through holes.

21.1 VISUAL INSPECTION

Even though the finished pc board can be inspected with the naked eye, an inspection magnifier lamp is an ideal aid. This instrument more readily allows the detection of flaws and results in less eye strain. The magnifier lamp has a circular 22-watt fluorescent tube which encircles an interchangeable magnifying lens. Typical lens powers are 3, 4, 5, 8, and 10 diopters (1.75 to 3.5×), which provide shadow- and distortion-free viewing. The lower-powered lenses are used for view

TABLE 21.1
Comparison of Lens Power and Magnification

Diopters	Magnification	Object Distance from Lens (in.)
3	1.75×	13
4	2.00×	10
5	2.25×	8
8	3.00×	5
10	3.50×	4
12	4.00×	3

ing a reasonably large area, while the higher-powered lenses are used for closer scrutiny of a smaller area or feature. See Table 21.1 for a comparison of lens power and magnification.

An inspection magnifier lamp used to inspect a pc board is shown in Fig. 21.1. The types of surface defects readily visible under a magnifying lamp are *broken* circuits and *bridged* circuits. Broken circuits are viewed as obvious interruptions in conductor paths such as that shown in Fig. 21.2a. These may be the result of improper handling of the taped artwork master or the phototools, opaque particles allowed to remain on the phototools, incomplete developing of the resist film, or scratched pattern-plated solder before the etching process. This type of defect must be repaired. If the number of such defects is not extensive and if it is permissible by company policy, the break can be repaired with bus wire. A piece of bus wire cut long enough to be laid along and span the broken path serves as a conductive bridge. Flux is applied to the paths on each side of the break and with the wire held in place, it is soldered to the broken ends of the conductor paths. The result of such a repair is shown in Fig. 21.2b. The flux should be completely removed after the wire has been soldered. (*Note:* This type of repair should be undertaken after the pc board is completely assembled and soldered.)

Bridged circuits appear as unwanted connections between any features in

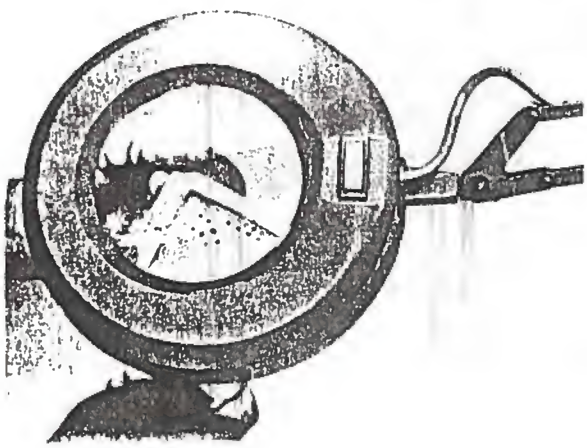

FIGURE 21.1. Inspection of pc board under magnification.

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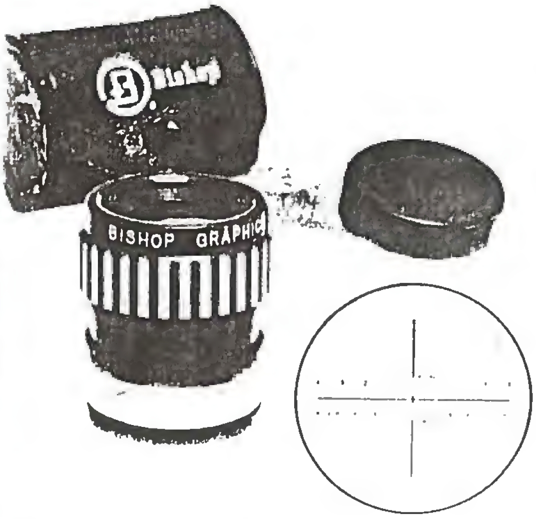
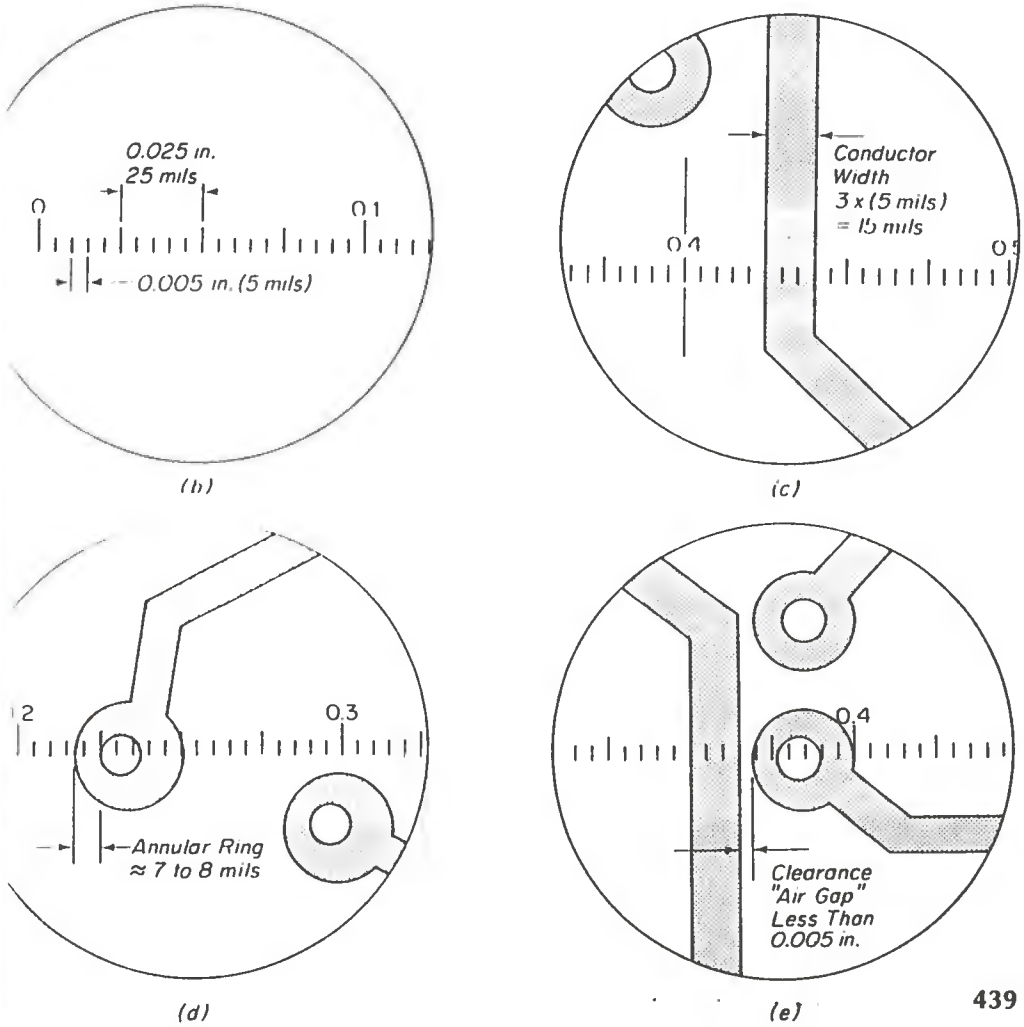


FIGURE 21.4. Measurements that can be made using a comparator: (a) 10× comparator, *courtesy of Bishop Graphics Inc., Westlake Village, Calif.*; (b) scaled reticule; (c) conductor width measurement; (d) annular ring measurement; (e) air gap measurement.



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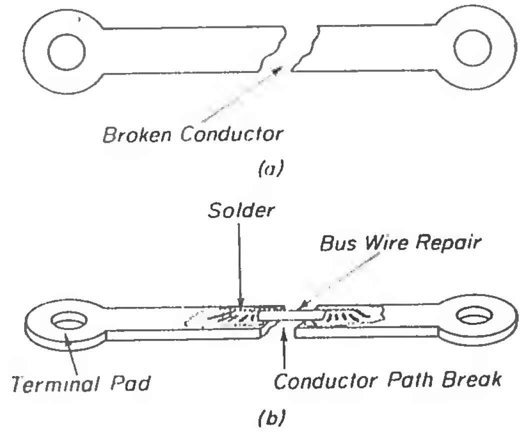


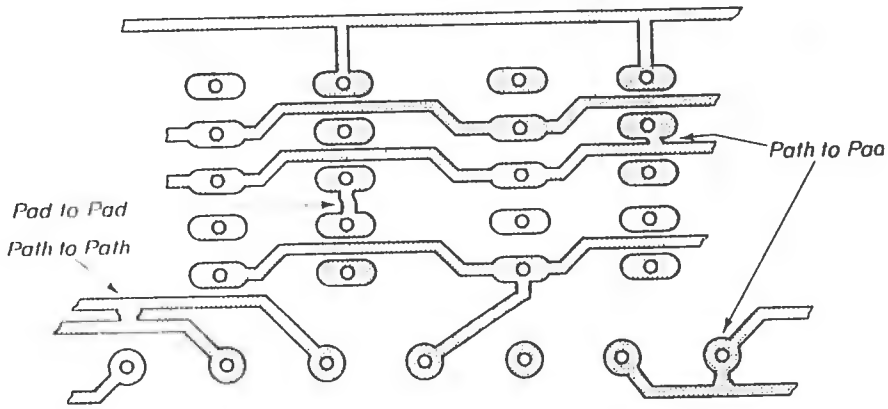
FIGURE 21.2. Typical conduc defect and repair: (a) open circu (b) one method to repair open c cuit.

the conductor pattern (see Fig. 21.3). These *shorts* are again primarily due improper handling of the artwork masters, the phototools, or of the imaged boar A scratch in the photo-resist can also cause these bridged circuits to form. permissible, these defects can be easily repaired by removing the unwanted me (solder over copper plating over laminate copper) down to the insulation surfa with a scalpel.

When visual inspection requires the precise measurement of the conduct pattern features, an important device used for this purpose is the 10× magnif called a *comparator*. This has a precisely scaled reticule such as the one show in Fig. 21.4a. As shown in Fig. 21.4b, the scale has 100-mil (0.1-inch) ma divisions with 25-mil (0.025-inch) subdivisions and 5-mil (0.005-inch) minor visions. The comparator is designed with a transparent 360-degree base to adr a maximum amount of light. It is used by simply centering its base directly o the feature to be measured. By careful alignment of the reticule on the featu its size can be precisely determined to within 5 mils and a good reading to witl 1 or 2 mils can be estimated.

The use of a comparator is shown in Fig. 21.4c, d, and e. Figure 21.4c sho the conductor path width being measured. Note that the width distance falls p

FIGURE 21.3. Examples of circuit bridges.



cisely on a minor subdivision, resulting in an exact measurement of 15 mils (0.015 inch). Figure 21.4d shows a comparator being used to measure the annular ring of a pad. Here the result is less precise since the dimensions of the feature span between minor divisions. However, a reading of approximately 7 to 8 mils (0.007 to 0.008 inch) can be closely estimated. Notice also in Fig. 21.4d that there is some misregistration of the pattern since the terminal pad is not centered on the hole as seen by the nonuniformity of the annular ring. Another example of the use of a comparator is the measurement of the air gap between conductor pattern features. This is shown in Fig. 21.4e, where a conductor path-to-terminal pad spacing is read as less than 5 mils. A minimum air gap of this dimension may be questionable as to its acceptability.

A severe imperfection on double-sided pc boards that can be detected by visual inspection is defects in hole wall plating. These *voids* are the absence of both solder and copper in random areas of the barrel (see Fig. 21.5a). These are often the result of excessive cleaning prior to pattern plating, incorrect processing of the deposition line, or a variety of other processing problems. Voids in a plated-through hole may well render the board useless. Usually, one or two random and isolated voids can be considered acceptable, but if they appear in the same hole, they most likely exist in all holes and in all boards processed in that batch.

Another form of void, also shown in Fig. 21.5a, is a *rim void* or *barrel crack*, which occurs at the interface of the surface of the hole and the top or bottom ends of the barrel. These cracks are totally unacceptable since they break the electrical continuity between both sides of the board.

Voids can often be detected with the naked eye by viewing the holes at a 45-degree angle to the board surface. A comparator may also be used to enhance the view. It is also placed at a 45-degree angle to the board surface (see Fig. 21.5b).

A special magnifier, used exclusively for the inspection of plated-through holes, is shown in Fig. 21.5c. This 8× magnifier has a center prism that splits the image of the inside of the hole into nine views that simultaneously show the entire surface area of the barrel without moving the instrument. It is simply placed flush to the surface of the board and centered on the hole to be inspected. Thus a 360-degree undistorted view of the barrel is achieved without rotating the board or the instrument.

Inspection of plated-through holes also detects foreign matter, such as dus and dirt, which may have resulted from drilling, or from nodulation (rough sur- face) caused by poor plating processes. Anything on the hole walls other than a smooth and continuous layer of metal is an indication of processing problems start ing with the drilling operation.

Highly sophisticated optical equipment is also available to improve the in spection of a pc board. One such instrument is shown in Fig. 21.6a. It is designe to project a magnified view of the pc board onto a large screen. It includes a microscope to permit even closer examination of any selected feature. This in spection system is equipped with an indexing x-y table onto which the board to b viewed is placed. The entire area of the board can be rapidly and systematicall scanned at as much as 25× magnification. Sufficient space is available to allo

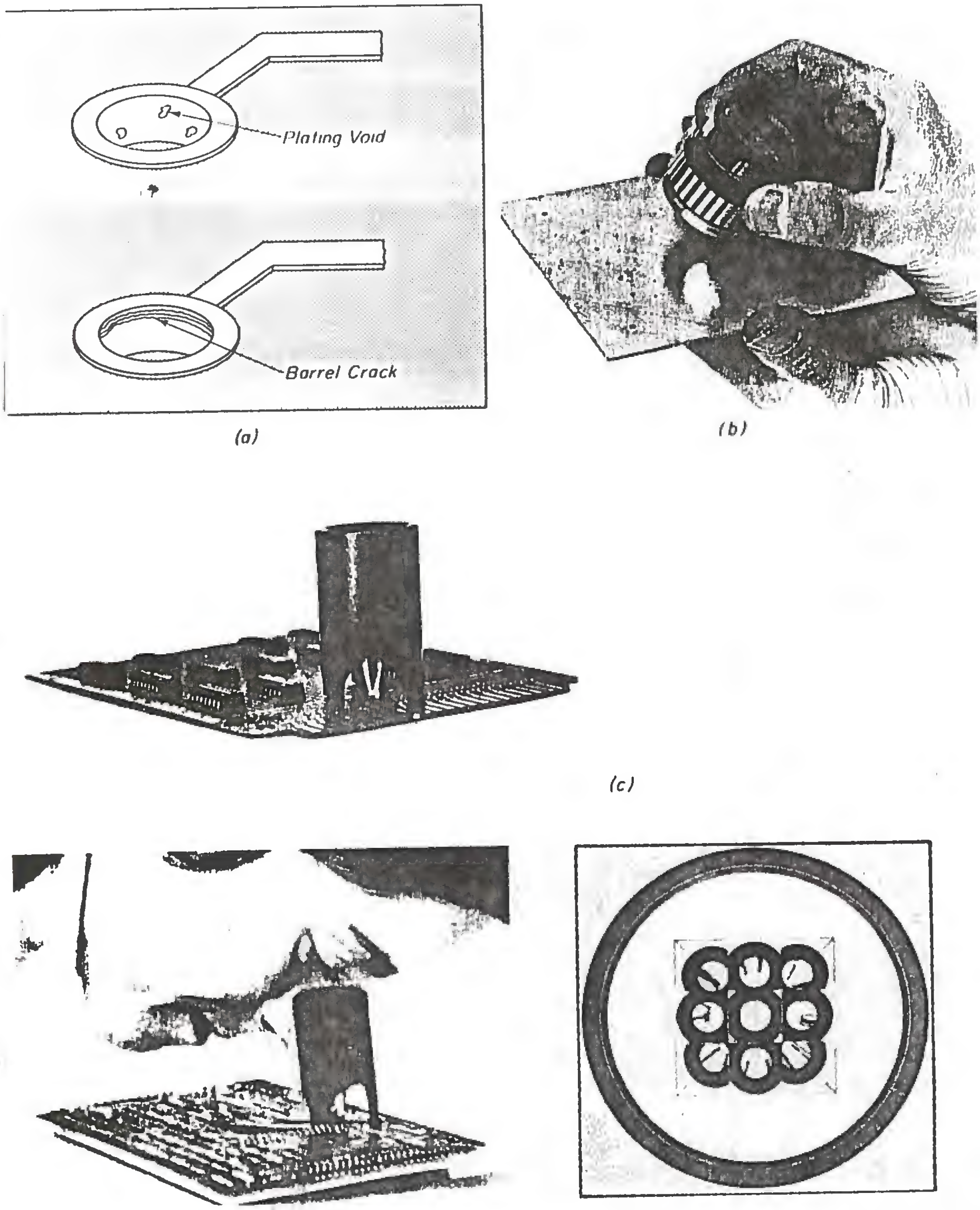
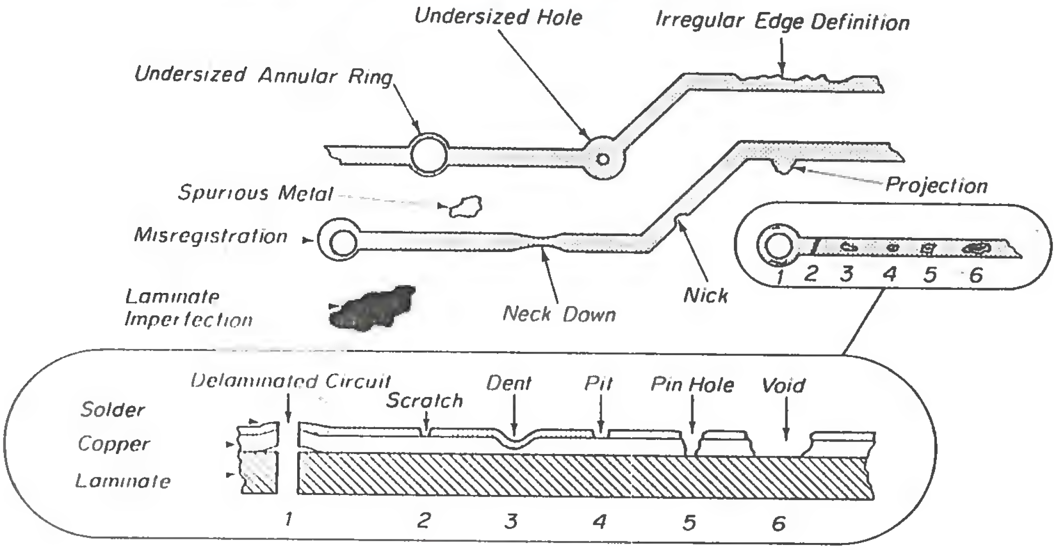


FIGURE 21.5. Plating defects and methods of visual inspection: (a) voids; (b) inspection using comparator at a 45-degree angle; (c) optical hole inspector, courtesy of *ALCHEMITRON*.

(a)

FIGURE 21.6. Defects are more readily found by magnified optical inspection: (a) optical inspection, *courtesy of Circuit Equipment Corporation, Baltimore, Md.*; (b) conductor pattern defects.



(b)

some minor repairs to be made within the viewing area. One of the advantages of this type of inspection system is that it can aid in viewing conductor pattern defects which may not easily be detected by eye or with the aid of low-magnification devices. Some of these defects, together with those previously mentioned, are shown in Fig. 21.6b. In addition to inspecting finished pc boards, these optical inspection systems may also be used to check and correct artworks and phototools. This greatly aids in preventing a number of board defects that might otherwise occur.

21.2 MECHANICAL MEASUREMENTS

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Mechanical measurements on pc boards may be grouped into two general categories: (1) the measurement of board length, width, and thickness, and (2) hole size measurement of both plated and unplated holes.

The length and width of the finished board should be measured with precision instruments such as the dial caliper shown in Fig. 3.9. This caliper is typically accurate to 0.001 inch, which is suitable for making board measurements. The results of the dial caliper readings should be compared with those of the dimension drawing of the board to determine if they are within the specified tolerance. For single- and double-sided boards, the length and width dimensions are critical, especially if the board is to slide into grooved guides, shown in Fig. 22.25, so that its fingers fit into an edge-line connector. On the other hand, if the board is designed to simply be installed into a chassis, such as our amplifier shown in Fig. 22.26, its dimensions are far less critical.

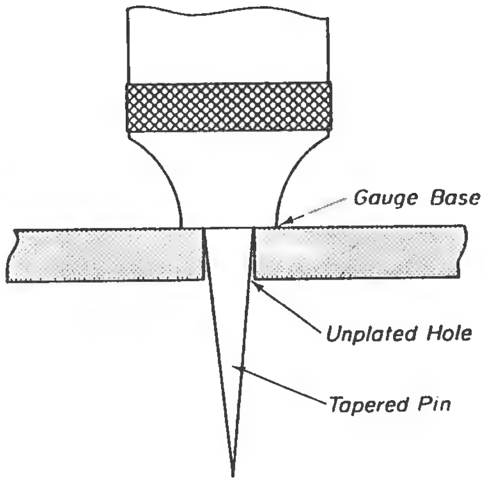
In the case of a multilayer board, the *thickness* dimensions are extremely important if the fingers are to fit snugly into a connector. To avoid mechanical or electrical problems, the board must not be thicker or thinner than the specified tolerance. Thickness measurements can also be accurately made with the dial caliper or with a micrometer, shown in Fig. 3.11. These measurements should be taken in the finger area to determine correct fit into the connector. To obtain the most accurate reading, only the *insulation* thickness should be measured, not a portion of the board that contains any copper pattern. If thickness measurements of all four corners of a multilayer board show a wide variation, the problem is usually the result of a fault in the press platens.

For the accurate measurement of unplated holes having straight sides (i.e., uniform top-to-bottom diameters) a *dial-indicating tapered-pin hole gauge*, such as the one shown in Fig. 21.7a, may be used. To measure the hole's diameter, the tapered pin is first inserted into the hole. The base of the gauge is then brought down flush to the insulation surface of the board (see Fig. 21.7b). The dial indicator is calibrated to read the hole diameter directly as a result of reading the diameter of the tapered pin at its top entry point. The gauge shown in Fig. 21.7a will provide a hole-diameter reading to an accuracy of 0.001 inch. Four different gauges of this type will give a full range of measurements from 0.010 to 0.330 inch, which represent drill bit sizes from No. 80 (0.35 mm) to $\frac{3}{8}$ inch (9.5 mm).

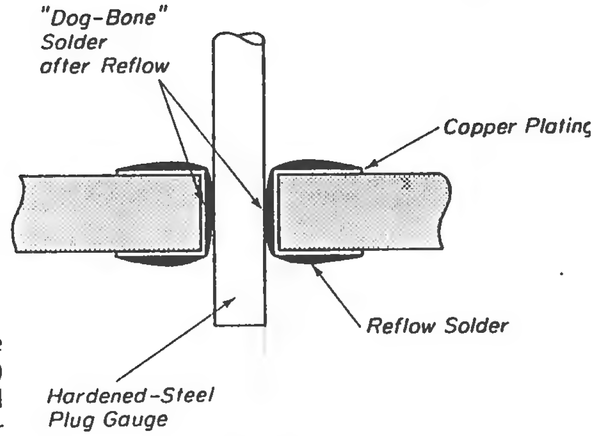
A cross-sectioned view of a drilled hole that has been plated and reflowed is shown in Fig. 21.7c. Note the *hourglass* or *dog-bone* effect of the plated metals. A major concern in plated holes is that the specified component leads fit into the holes without any degree of difficulty. Accurate measurement will determine this in addition to ensuring that proper plating thickness has been achieved. To measure the minimum diameter of these nonuniform barrels, a set of untapered plug gauges, having accurate and uniform diameters, must be used. Typical sets of plug gauges for this application, such as those available from the Meyer Gauge Company,* consist of a series of 2-inch microfinished hardened-steel pins. One set ranges in size from 0.011 to 0.060 inch in diameter, increasing in increments

*Meyer Gauge Co., 230 Burnham St., South Windsor, CN 06074.

(a)



(b)



(c)

FIGURE 21.7. (a) Tapered-pin hole gauge, *courtesy of ALCHEMITRON*; (b) measurement technique for unplated holes; (c) measurement technique for plated holes.

of 0.001 inch. Another set ranges from 0.061 to 0.250 inch, increasing in the sam increments. The size of pin which when inserted into the hole will meet extremel slight resistance or drag indicates the hole's diameter. These pins must be use with care. If even moderate pressure is required to insert a pin into the hol€ damage to the plating could result.

21.3 ELECTRICAL MEASUREMENTS

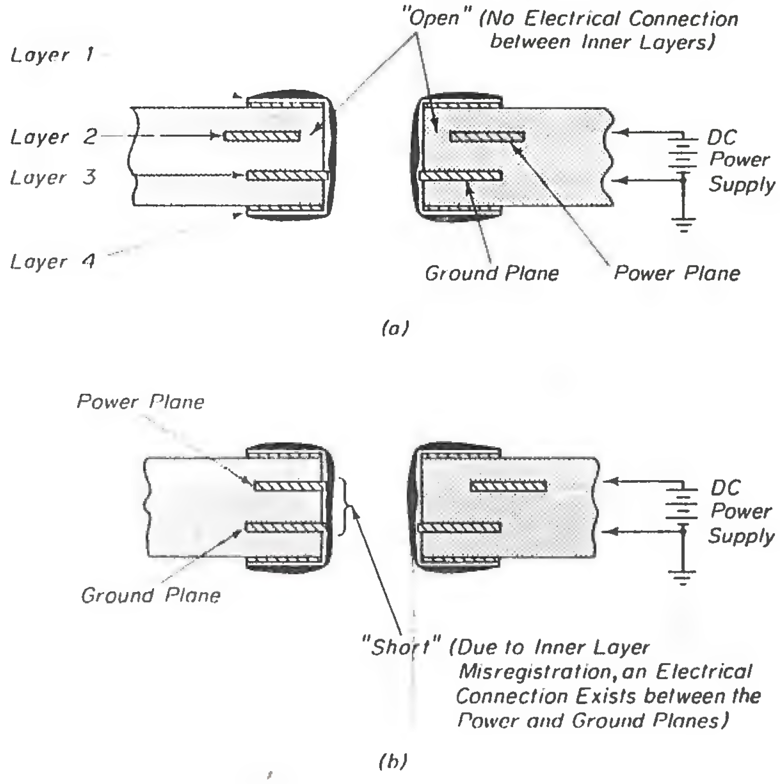
One of the primary concerns in a finished pc board is that no unwanted shorts (opens exist. For relatively uncomplicated designs, visual inspection, as previousl discussed, is suitable for detecting these faults. A great deal of difficulty is e countered, however, in the inspection of high-density double-sided and multilay(boards. For these levels of designs, it is beyond effective visual inspection, eve

if aided with optical equipment. After initial visual and mechanical inspection, computer-based test equipment designed to automatically test the entire circuit for proper continuity is employed. Other electrical instruments are also used to measure the average thickness of the copper deposited on the barrels of plated-through holes.

In multilayer boards, severe misalignment of inner layers may cause, for example, a power layer to be shorted to a ground layer (see Fig. 21.8a). Note that proper alignment of inner layers 2 (power) and 3 (ground) results in the power layer connected to the barrel and an open circuit existing between it and the ground layer. Thus, a power source connected across these two layers will not be shorted. The problem resulting from the misalignment of layer 3 (ground) is shown in Fig. 21.8b. Here, ground makes electrical connection to the barrel, resulting in its being shorted to layer 2 (power). Because the power and ground layers are connected through the barrel, a power source connected to these points will be placed across a direct short.

For the reasons just stated, one of the most basic electrical tests made on multilayer boards is to check for *inner-layer shorting*. This type of test is not intended to measure the degree of misalignment but determines the acceptance

FIGURE 21.8. Testing for an internal short circuit in an MLB: (a) properly aligned inner layers; (b) misregistration of power plane.



or rejection of a board. The only instrument required is an ohmmeter. After zeroing the meter, one test probe is brought into contact with an outer-layer terminal of the board which is connected, through a plated hole, to layer 2 (power). The second meter probe is made to contact an outer-layer terminal pad that connects to layer 3 (ground) through another plated hole. A reading of *infinite ohms* (i.e., an open circuit) should be read on the ohmmeter which indicates an acceptable board. This reading shows no electrical connection existing between layers 2 and 3. Power can safely be applied to this board. If, however, the ohmmeter reads *zero* ohms (i.e., a short circuit between power and ground layers), the board must be rejected because of inner-layer misregistration. Any power applied to these inner layers will result in the supply being shorted, causing fuses to blow, circuit breakers to trip, and so on.

Recent demand for higher-density boards and the number of layers required in one board has resulted in it becoming impossible to test, with 100% accuracy, the electrical integrity of the total pattern. The use of the most sophisticated visual inspection techniques coupled with mechanical tests and electrical checking with meters is found to be unsuitable for high-density, ultra-fine-line boards. Not only is this type of testing extremely time-consuming, but only 50 to 70% of faults in a multilayer board are detectable, due to human limitations. To overcome these shortcomings and to develop test equipment more compatible with the state of the art, manufacturers have developed a new concept in the electrical testing of bare boards (i.e., boards that have no parts mounted). This automated test equipment (ATE) uses a computer which can be programmed to quickly and repeatedly test 100% of the conductor pattern on any level of the board. It can locate faults (shorts or opens) and identify the type of fault. *Bare-board testing* equipment is classified as either *dedicated* or *universal* systems. They are intended for the testing of large volume work and not for prototype applications.

A bare-board pc board test system is shown in Fig.21.9a. It consists of a microprocessor-based computer connected to a multiple-contact test fixture or head through a wire cable system. Additional equipment required is an external vacuum pump to activate the test head and a printer to provide a readout of the test results. The test head is manufactured to test a specific circuit board pattern (dedicated) or designed to test any pattern (universal). A universal text fixture is far more expensive than the dedicated type. For both text fixture designs, the head consists of a series of spring-loaded test probes or *nails*. They are press-fitted into an insulated base plate in a pattern which aligns each nail to make contact with each terminal pad of the conductor pattern. Several styles of test probes are shown in Fig. 21.9b. The probe with the *serrated* top is the one used in the tester shown in Fig. 21.9a. This style makes a firm electrical contact on its assigned terminal pad. The other end of the probe is connected to a lead in a cable which is connected to the computer. The cable provides the electrical connections between the individual terminal pads and the microcomputer.

A second insulated panel rides on guide pins secured to the base plate. This panel is provided with a clearance hole for each contact point (i.e., pad) and is

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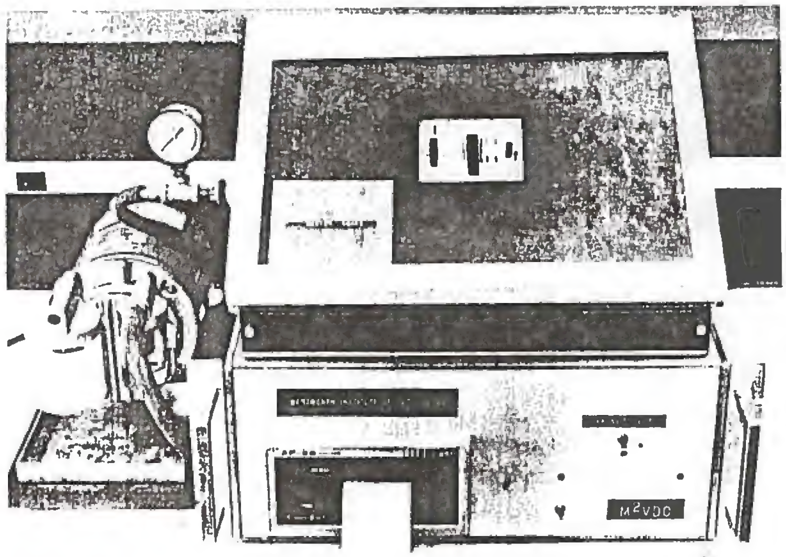
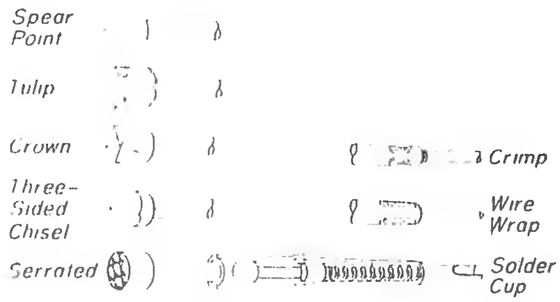


(a)



(b)

FIGURE 21.9. (a) Bare-board test system; (b) styles of contact pins.

fitted with tooling pins for registering the board to the *bed of nails* (see Fig. 21.10). After the pc board is positioned onto the tooling pins, a sheet of surgical rubber is placed over the head to create a vacuum seal on the board. When the vacuum system is activated by computer, the board is forced downward onto the bed of nails to make electrical contact with each terminal pad.

A dedicated test head has test pins located below each individual terminal pad for a specific conductor pattern only. On the other hand, a universal test head has a test probe positioned on a grid spaced at 0.1-inch intercepts. Large universal

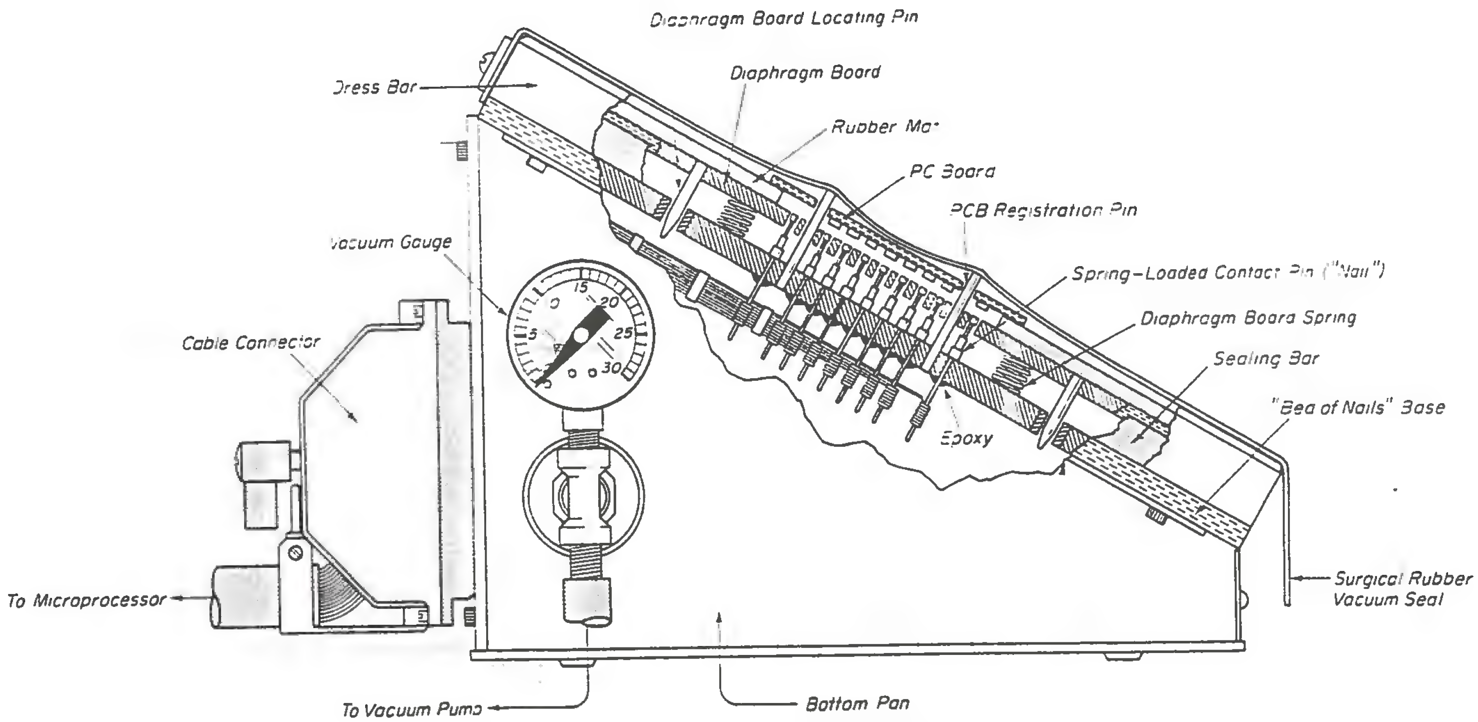


FIGURE 21.10. Sectional view of test head.

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test systems may have a matrix of as many as 40,000 probes (20- by 20-inch grid). With this type of system, any board design may be tested as long as its terminal pad centers are located on a 0.1-inch grid and the tooling holes on the board are made to align with the tooling pins on the fixture. To test a specific conductor pattern on a universal test system, a plexiglass plate with a hole image that matches the terminal pad locations is positioned between the probe matrix and the board. This allows only those probes that align with pads to make contact with the board, while the other probes are blanked out.

The bare-board tester, shown in Fig. 21.9a, has two modes of operation. These are the *learn* mode and the *test* mode. When power is initially applied to the microcomputer, the system is in the *learn* mode. A pc board having a predetermined correct conductor pattern is placed on the test head. The *press to test* button is depressed, which activates the vacuum system and causes the board to be pressed against the probes. The microcomputer then samples each test probe and stores in its memory the number assigned to each probe, its terminal pad position, and the correct conductor path interconnection sequence. The microcomputer has thus sampled each test probe and *learned* the electrical continuity map of the correct master board. This board is then removed from the test fixture and the system is ready to electrically test boards which have been processed with the same conductor pattern as the master board. A board to be tested is placed on the fixture and the *press to start* button is again activated. The contacting probes feed information to the computer, which compares the conductor pattern of this board with that of the master board stored in memory. The results of this test are printed on a paper tape which indicates if the unit under test is acceptable (no shorts or opens) or if there are any faults. Any shorts or opens are specified together with their locations by identifying the assigned numbers of the terminal pads involved (see Fig. 21.11a). To most efficiently make use of the tape readout in locating any faults on the board, a layout of the conductor pattern, together with the assigned terminal pad identification numbers, is essential. This is shown in Fig. 21.11b. It can be seen that a bare-board testing system is quick and repeatable with a consistent degree of accuracy.

Automatic test equipment is also available which will quickly and nondestructively measure the average thickness of the copper plated onto the barrel of a plated-through hole. One such system is shown in Fig. 21.12a. This computerized tester is called the *Caviderm CD7* and is manufactured by UPA Technology, Inc. The Caviderm makes a microresistant (μR) measurement which can be used to nondestructively test both the quality as well as the plating thickness of a plated-through hole. The equipment consists of two self-centering conical contacts which touch the top and bottom rim of the hole (see Fig. 21.12b). The *current injection cones* apply a precisely known current (usually 20 mA) through the copper plating which makes up the hole wall. The resulting voltage drop developed across the hole is detected by the *voltage pickup contacts*. Electronically, the voltage developed is divided by the current injected to result in micro-ohms of resistance ($R = V/I$). The computer processes this data and translates it automatically into barrel thickness, shown on a digital display in mils. This method of test actually measures the *average* resistance or *average* thickness of the barrel. For this rea-

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INSTRUCTIONS FOR
LOADING DATA

THE MICROCOMPUTER
SYSTEM IS READY TO
LOAD DATA FROM THE
MASTER PC KEYBOARD.

PLACE THE MASTER PC
BOARD ON THE BED OF
NAILS AND DEPRESS
THE "PRESS TO TEST"
SWITCH.

  2
M VDC
```

Results of learn mode

```
WENTWORTH   INSTITUTE
   OF   TECHNOLOGY

ELECTRONIC  SHOP
BARE   BOARD   TESTER

THE PC BOARD NOW
BEING TESTED HAS
NO WIRING ERRORS.
JOB WELL DONE.
```

Results of correct PC board

```
WENTWORTH  INSTITUTE
   OF   TECHNOLOGY

ELECTRONIC SHOP
BARE  BOARD  TESTER

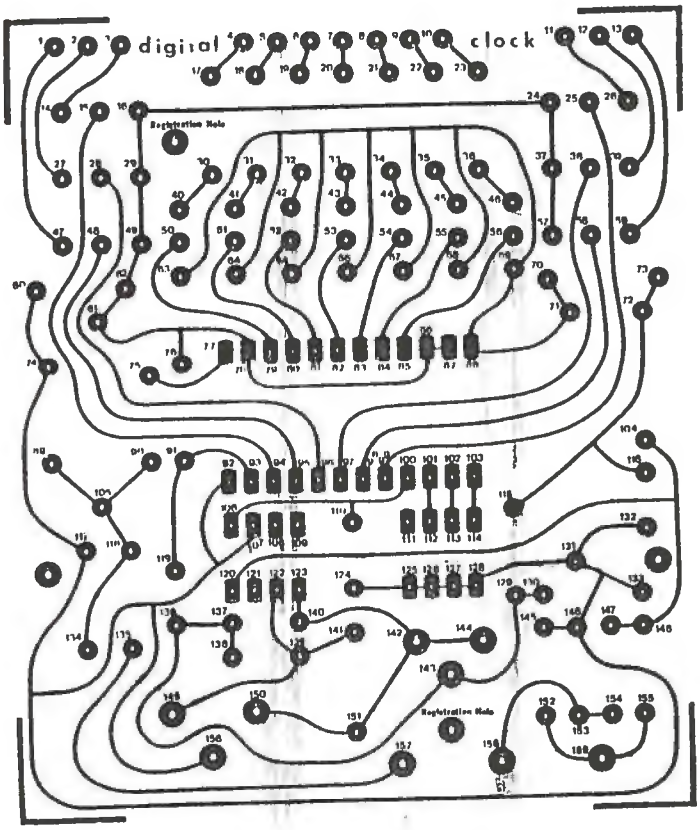
6 WIRING ERRORS

DRIVE ERROR TYPE OF
PIN   POINT  ERROR

 12--   13---SHORT
 12--   59---SHORT
 13--   39---SHORT
 39--   59---SHORT
100--  110---OPEN
106--  110---OPEN
```

Results of PC board with six errors

(a)



(b)

FIGURE 21.11. Bare-board conductor pattern code and results of automatic testing: (a) bed of nails printouts; (b) terminal pad identification.

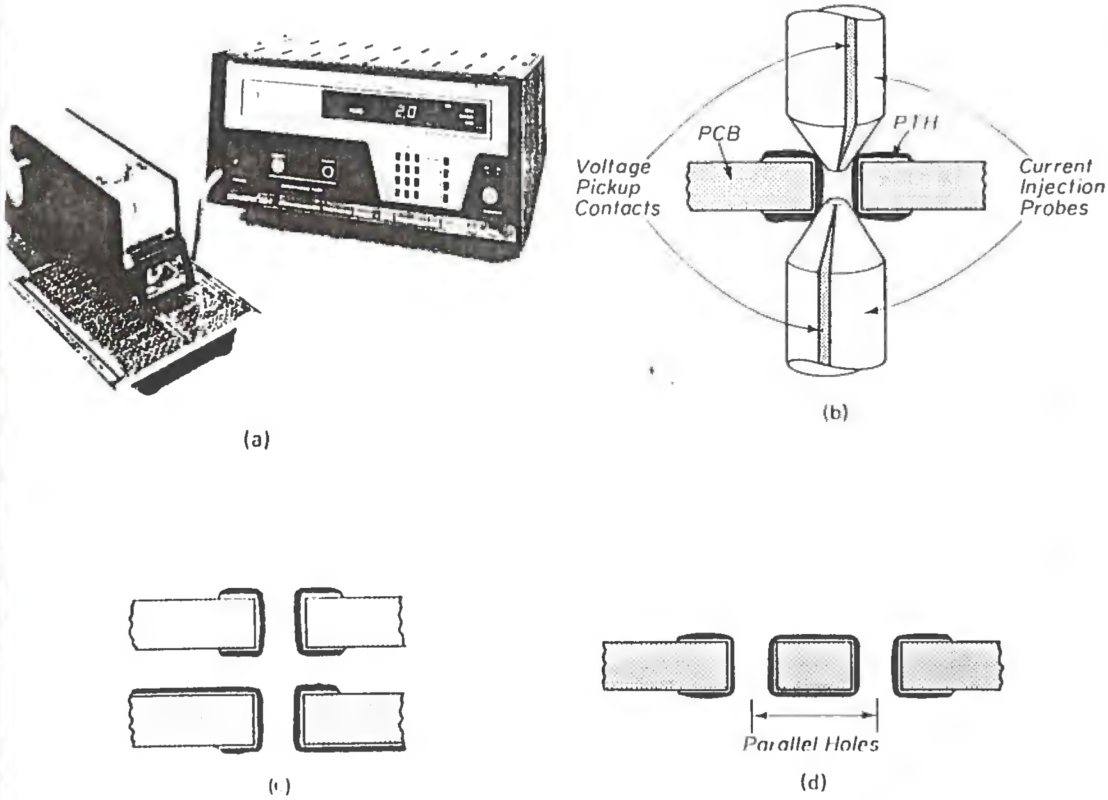


FIGURE 21.12. Nondestructive testing of plated-through holes: (a) Caviderm, *courtesy of UPA Technology, Inc.*; (b) self-centering conical test probes; (c) isolated PTHs do not result in parallel paths; (d) parallel holes closer than $\frac{1}{4}$-inch spacing will result in incorrect readings.

son, any voids, cracks, or thin spots will strongly influence the reading. The net result will be lower values of wall thickness displayed than those specified or that would result if these defects were not present. In testing of plated-through holes in either double-sided or multilayer pc boards, the measurement is essentially the copper thickness and is not really effected by the solder layer above the copper. The measurement can, however, be misleading if not performed correctly. For measurements to be accurate, an *isolated* hole must be used. Shown in Fig. 21.12c, an isolated hole is one that has either no circuit etches (top or bottom) leaving the hole, or any hole having interconnecting terminations that do not result in a parallel circuit. An inaccurate reading will also result if the hole to be measured forms a parallel circuit with a hole closer than $\frac{1}{4}$ inch (see Fig. 21.12d).

The Caviderm CD7 tester is self-calibrating. All that is required to initiate the measurement is to key into the computer the board thickness and the hole diameter.

21.4 MICROSECTIONING

All of the pc board inspection and test techniques discussed to this point are nondestructive, that is, the board has not been physically damaged in any way. These tests are essential for ensuring a degree of quality control. However, nondestructive testing falls short in providing the product user or the manufacturer a complete assurance of the quality of the finished pc board. This assurance can only result through a destructive cross-sectioning test procedure called *microsectioning.* In this type of test, a sample board from a production lot of double-sided or multilayer boards is destroyed in order to accurately view the interior walls of a plated-through hole to determine its quality. Microsection testing can also be performed using a specially prepared sample, called a *coupon*, which does not require that a finished board be sacrificed. This nondestructive microsectioning test will be discussed in conjunction with specimen selection procedures.

Visual inspection of the cross-sectional view of the barrel of a typical plated-through hole requires the use of a microscope having a minimum of 50× magnification. This highly magnified view allows the electrical integrity of the interconnection points between the top and bottom ends of the barrel to be more accurately evaluated. Plated-through holes are the most critical processes in the fabrication of a pc board. Continuous metal must be formed through the hole and over the original copper outer surface.

Microsectioning aids in evaluating a variety of plated-through-hole characteristics, including barrel copper and solder thickness, voids, barrel cracks (rim voids), nodulation (rough plating), annular ring, conductor width, multilayer board registration, epoxy smear, and etchback. (These defects and their appearance will be discussed later in this section.) The visual evaluation of these characteristics provides the end product user with a more definitive representation of the quality of the finished board. Used as a means of quality control, microsectioning tests are an early warning indicator to the manufacturer in determining potential processing problems. If allowed to go undetected, these problems can dramatically reduce the yield of acceptable boards.

The following steps outline the microsectioning process:

1. *Specimen selection and removal*—A sample plated-through hole is selected and then removed from the board with a punch.
2. *Cross-sectional cutting*—The cross-sectional side view of the hole is prepared for inspection by sawing through the center of the hole using a diamond saw.
3. *Specimen mounting*—The cross-sectional view is positioned in a mold which is next filled with an epoxy mounting material and allowed to harden. The epoxy-mounted sample is then removed from the mold.
4. *Sanding and polishing*—The surface to be inspected is sanded and then finely polished to a smooth finish.
5. *Specimen etching*—The area to be inspected is lightly etched to remove any smearing of the two metals (copper and tin–lead) so that they may be clearly distinguishable.

6. *Microscope inspection*—The specimen is now ready to be viewed on an inverted microscope.

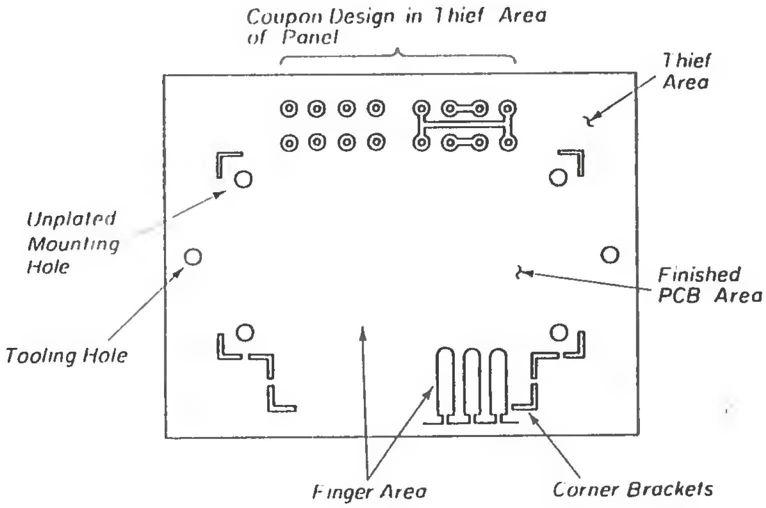
Each of these steps will be discussed in detail followed by an evaluation of several illustrations showing typical plated-through hole faults.

Specimen Selection and Removal. The selection of a sample specimen may be made from the image area of a pc board or from a specially prepared coupon within the thief area (see Fig. 21.13). Those selected from the image area will result in the board being destroyed. Samples taken from the thief area will not damage the board, allowing it to be returned to the usable lot. It is thus apparent that there is a substantial cost advantage in selecting samples from coupons in the thief area. The disadvantage, however, is that the thief area is the section of the board having the highest current density. This will result in a hole having a larger plating thickness than one appearing in the image area. Either sample will show essentially the same degree of plating quality and registration.

Which of the sample areas to select becomes a trade-off of cost versus inspecting a more representative sample (i.e., taken from the image area). This trade-off usually results in inspecting for plating quality and registration by using thief area coupons and occasionally destructively sampling a hole from the pattern area to monitor copper and solder thickness.

Specimen Removal. When removing the plated-through-hole sample from the pc board, extreme care must be exercised to avoid damaging the plating. Any deformities or cracks resulting from its removal will render the sample useless in evaluating the quality of the plating. Specimen holes may be removed by sawing, shearing, or punching. On 0.059-inch boards, punching is the method most often

FIGURE 21.13. Test coupon provided in thief area eliminates board destruction.



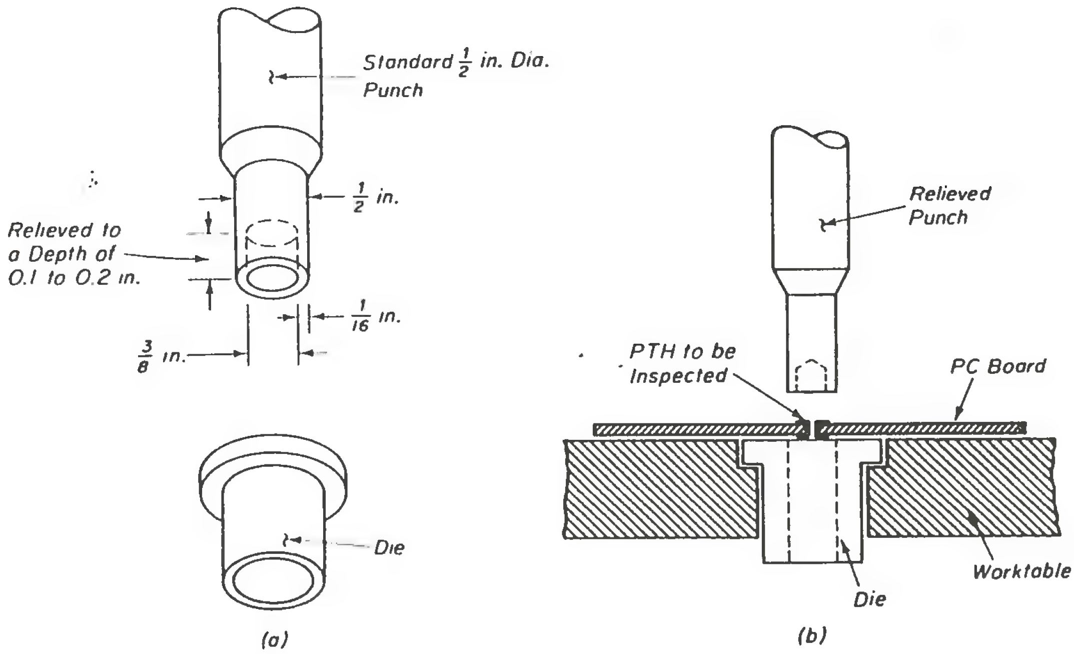
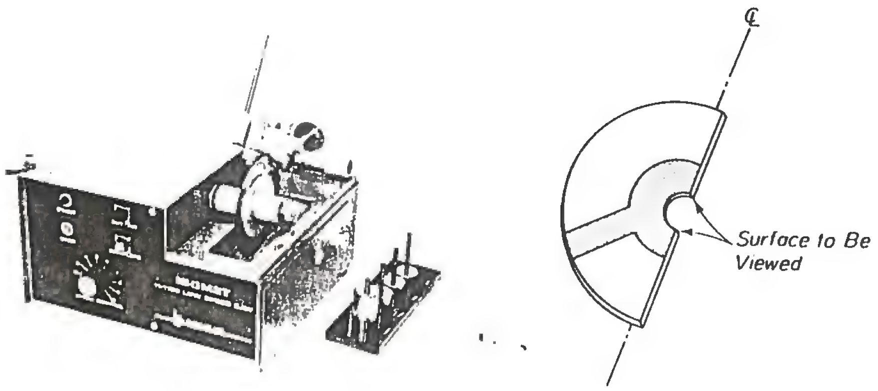


FIGURE 21.14. PTH specimen removal by punching: (a) specifications for relieved punch for specimen removal; (b) removing sample PTH for inspection.

used. A specially prepared *strain relief* punch and standard die, as shown in Fig. 21.14a, are required. The diameter of the punch should be at least ½ inch with a ⅛-inch diameter relieved center having a depth of 0.1 inch. This arrangement can be used in a single-station punch press or a standard lever-operated turret punch such as that shown in Fig. 6.15. To remove the sample, the board is positioned in the machine between the punch and die as shown in Fig. 21.14b. With the specimen hole centered under the relieved section of the punch, it is removed from the board with no damage resulting to the barrel plating. This method of specimen removal is quick, easy, and effective.

Cross-Sectional Cutting. With the specimen removed, it is next cut through the hole slightly below its center line using a precision cutoff saw fitted with a diamond-coated abrasive blade. A typical saw used for this purpose is shown in Fig. 21.15a. The sample is firmly clamped into the cutoff arm in a precise position over the blade so as to bisect the hole. A micrometer adjustment is used for this positioning. The cutoff arm is weighted with approximately 75- to 100-gram weights in order to apply an adequate downward pressure of the sample against the saw blade during the cutting operation. The speed of the blade rotation is set to about 75 rpm. (This corresponds to a setting of 3.5 on the unit shown in Fig. 21.15a.) The sample is then gently lowered until it rests against the rotating blade. The bottom edge of the blade is continuously immersed in a mineral oil cooling



(a) (b)

FIGURE 21.15. Cutting specimen to expose cross section of PTH with a diamond saw: (a) diamond saw; (b) cut specimen.

bath in order to avoid the generation of heat during the cutting process, which could adversely affect the appearance and characteristics of the hole plating. With this type of cutting arrangement, bisecting of the sample takes between 2 and 3 minutes and results in an extremely smooth-cut edge. After the cut is complete, the saw will automatically shut off. The sample is then withdrawn from the clamp and washed in alcohol to remove all traces of the coolant. The cut sample is shown in Fig. 21.15b.

Specimen Mounting. To prepare the specimen for sanding and polishing, it is encapsulated in an appropriate mounting compound. This begins by positioning the sample against a piece of glass with the hole to be viewed (i.e., the cut edge) facing the glass. It is secured in this position with a retaining spring, as shown in Fig. 21.16a. A plastic mounting ring, which has been sprayed with a silicon-base mold-release agent, is then centered around the sample. To prevent damage to the outer-layer plating during the sanding and polishing process, the mounting ring is filled with an encapsulating compound. This also provides support to the cut edges of the plated hole. The encapsulating material must be a cold-mounting compound that will harden quickly. Materials that require high pressure and elevated temperatures are unsuitable for pc board inspection applications since they can damage the plating. A product called Quick MOUNT* is an effective cold-application compound consisting of a powder and a liquid resin. To mix this material, 1 part by volume of the liquid resin is poured into a paper cup and 2 parts of the powder are added. This is stirred with a spatula for at least 1 minute to result in complete mixing. The compound is slowly poured into the mounting ring until it is almost full. To prevent the sample from moving while the compound is being added, it may be held in place with a thin rod (see Fig. 21.16b). The filled mounting ring is then allowed to stand undisturbed for a min-

*Trademark of Fulton Metallurgical Products Corp., Saxonburg, PA.

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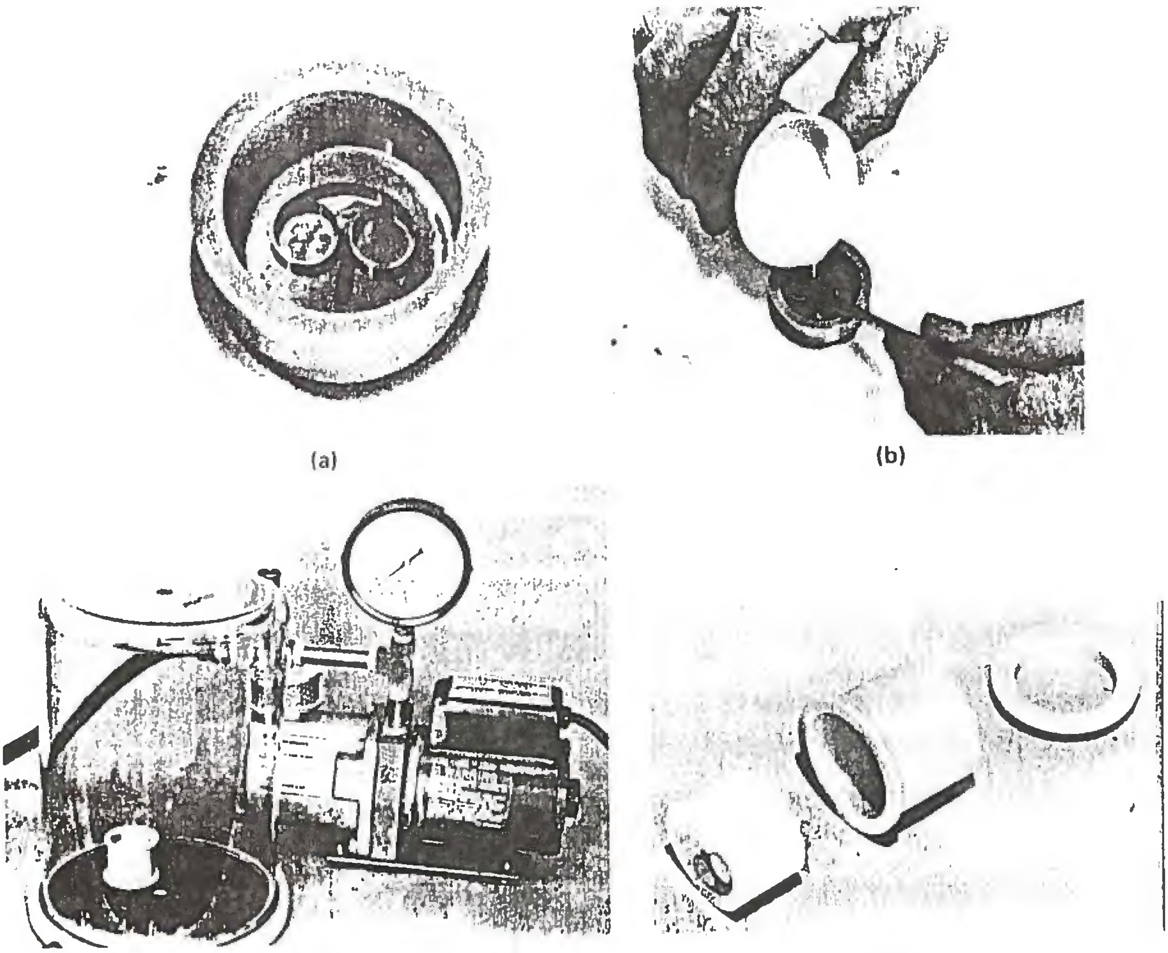

(a) (b) (c) (d)

FIGURE 21.16. Specimen mounting in preparation for sanding and polishing: (a) plastic mounting ring with specimen; (b) mounting compound must cover specimen and retaining ring; (c) vacuum pump may be used to remove bubbles generated in the mounting compound; (d) completely cured sample.

imum of 30 minutes at room temperature. The mixing of cold-mounting compounds may cause air bubbles to be generated throughout the material. These air bubbles should be removed since they can become lodged around the cut edges of the hole and provide no support of the plating, causing possible misinterpretation of the examination results. The air bubbles may be effectively removed from the compound by placing the glass plate and sample into a vacuum bell jar immediately after the mounting ring has been filled. The vacuum pump is then activated for a maximum of 10 to 15 seconds. The sample is allowed to remain in the bell jar for the 30 minutes to allow the compound to cure (see Fig. 21.16c).

After the curing cycle, the sample is removed from the bell jar and from the glass. Finger pressure is applied to the plastic mounting ring to remove the sample (see Fig. 21.16d). The mounted sample is now ready to be sanded and polished.

Sanding and Polishing. This is a multistep operation which begins with a coarse sanding and is completed to a highly polished surface. Although sanding is often done by hand on *lapping* blocks (four stationary sanding blocks ranging from 240 to 600 grit), semiautomatic sanding and polishing machines, such as the one shown in Fig. 21.17, are widely used. When used for sanding, four different discs (240, 320, 400, and 600 grit) having adhesive backings are applied to separate wheels. Sanding begins with the 240-grit wheel being placed into the machine. The mounted sample is then placed into a retaining ring that is attached to a motor-driven arm. Steel weights totaling approximately 200 grams are placed on top of the sample to provide a good degree of downward pressure. This is necessary to prevent the sample from rocking, which would result in a nonflat surface. A small stream of water flows continuously from a nozzle to prevent overheating of the sample during the sanding operation. The machine is set at a rotating speed of 300 rpm for the 240-grit wheel. The arm to which the sample is attached moves in a back-and-forth direction as the wheel spins. This results in a figure 8 sanding pattern which duplicates that of sanding by hand. The sample is sanded on this coarse wheel for approximately 2 minutes, after which it is successively sanded on the 320-, 400-, and 600-grit wheels in an identical manner to that described. For these less coarse grits, however, the rotating speed of the wheel is increased to 600 rpm and the sample again sanded for approximately 2 minutes on each wheel. It is essential that the sample be thoroughly rinsed under cold tap water between each change of grit wheel to remove any remaining coarser grit particles from its surface.

After the sample has been sanded on the 600-grit wheel, it is rinsed with water and inspected for flatness. In addition, the sanded surface should display only 600-grit sanding scratches. With the sanding process completed, the sample is ready to be polished.

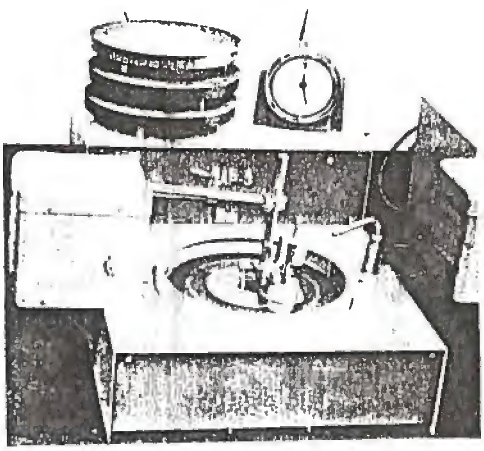

FIGURE 21.17. Semiautomatic sanding unit for initial sample preparation.

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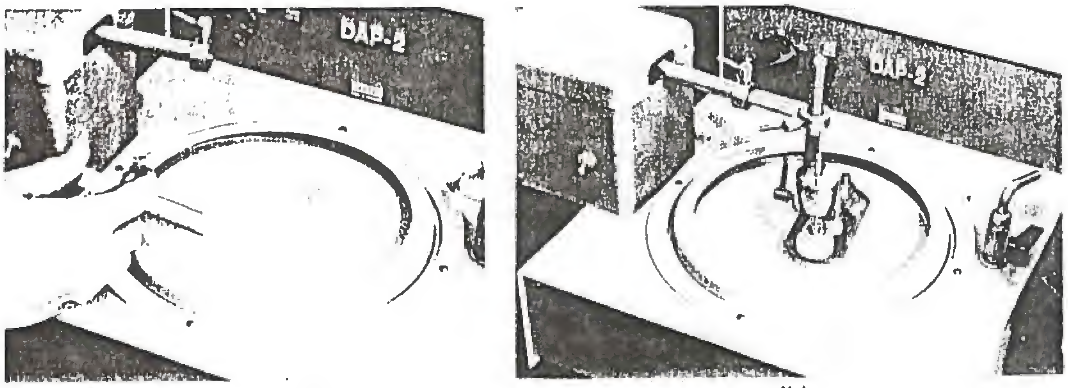

(a) (b)

FIGURE 21.18. Semiautomatic polishing: (a) application of diamond paste to Texmet polishing cloth; (b) diamond polishing at 250 rpm.

Polishing of the sample is done in two phases, which are (1) *diamond* polishing (coarse) and (2) *alumina* micropolishing (fine). Coarse polishing with a diamond abrasive compound will remove all scratches produced by the 600-grit sanding process and will result in extremely fine surface scratches which are barely detectable by the naked eye. Fine polishing with an alumina compound removes these minute scratches and results in an ultrasmooth surface, free of any visual blemish.

The semiautomatic machine shown in Fig. 21.17 is also used for polishing. Coarse polishing requires a napless polishing cloth, such as a Texmet* disk, to be initially applied to the wheel. This cloth is secured to the wheel by its self-sticking adhesive backing. A diamond paste, such as Metadi* diamond compound, which has a maximum particle diameter of 1 micron (0.001 mm), is spread sparingly in a star arrangement over the polishing cloth (see Fig. 21.18a). The most appropriate lubricant and extender for diamond polish is a lapping oil, such as Metadi fluid. A small amount of this oil is added to the diamond paste and polishing cloth. The polishing machine is next turned on and set to a rotating speed of 250 rpm. The sample is placed in the retaining ring and weighted as described previously (see Fig. 21.18b). Note that water is not used in this polishing process. Satisfactory diamond polishing is completed in 2 to 4 minutes with this arrangement. With the completion of this coarse polishing process, the sample is removed from the machine and rinsed thoroughly with tap water. Contact with fingers on the polished surface should be avoided while handling the sample.

Fine polishing requires a napped polishing cloth, such as AB Microcloth,* to be applied to a second polishing wheel. This cloth also has a self-sticking adhesive backing. The diamond polishing cloth and wheel are removed from the machine and replaced with the second wheel with the napped cloth. Fine polishing is accomplished with a 0.3-micron (0.0003-mm) alumina abrasive, such as AB

*Trademarks of Buehler Ltd., Evanston, IL.

Alpha Polishing Alumina,* in a water slurry. A small pool, approximately the size of a half-dollar coin, of this abrasive is deposited on the polishing cloth. This alumina abrasive requires no lubricants or extenders since they are contained in the slurry. Fine polishing requires a wheel rotation speed of 600 rpm and the sample again weighted with the same weights. This final polishing process requires only approximately 1 minute to result in an ultrasmooth polished sample. After completion, it is removed from the machine and rinsed in tap water, again avoiding finger contact with the polished surface. The viewing surface appears smooth and shiny and is ready for the final step in preparing the sample for inspection.

Specimen Etching. The polishing processes cause a slight smearing of the copper and the solder platings of the microsectioned sample. In order to remove the smears so that each of these plated metals will be clearly distinguishable for inspection, a light etching is required. The liquid etch for this purpose is prepared in a petri dish by mixing 3 parts of 26% ammonium hydroxide with 1 part of 3% hydrogen peroxide. The polished surface of the sample is immersed in this mixture for approximately 30 seconds at room temperature. The ammonium hydroxide will attack the smeared copper while the hydrogen peroxide will attack the solder to result in a microfinished sample ready for microscope inspection. The sample should be thoroughly rinsed and blow-air dried before placing it on a microscope. Finger contact with the polished surface must be avoided.

Microscope Inspection. To effectively view the polished specimen, a standard inverted-type metallurgical microscope, such as the one shown in Fig. 21.19, is recommended. This microscope consists of (1) stage/clamp and stage adjustments, (2) eyepieces, (3) five objective lenses on a rotating nosepiece, (4) light source and internal adjustable power supply, (5) 35-mm and Polaroid camera mount, (6) internal exposure meter, and (7) large-format viewing screen. An inverted type of microscope is recommended so that the polished surface of the sample may be placed against the stage and viewed through the objective lens located below the stage. The cross-sectional area of the hole is centrally positioned in the center of the stage and held firmly in place with a spring clip as shown in Fig. 21.19. For inspection of all parts of the sample, the stage may be moved left to right and front to back by vertical and horizontal *stage control knobs*. Concentric coarse- and fine-focusing knobs adjust the height of the stage.

The microscope can be used with *minocular* or *binocular* eye pieces with a *filar*. Filars are available with magnifications of 5×, 10×, and 15× and are used together with the magnification of the objective lens to determine the overall viewing magnification. Objective lenses have typical magnifications of 2.5×, 5×, 10×, 20×, 40×, and 100×. The revolving nosepiece holds five objective lenses for convenience in quickly changing magnifications. It can thus be seen that with the microscope described, magnifications can range from as low as 12.5× (2.5 × 5) to a high of 1500× (15 × 100).

*Trademarks of Buehler Ltd., Evanston, IL.

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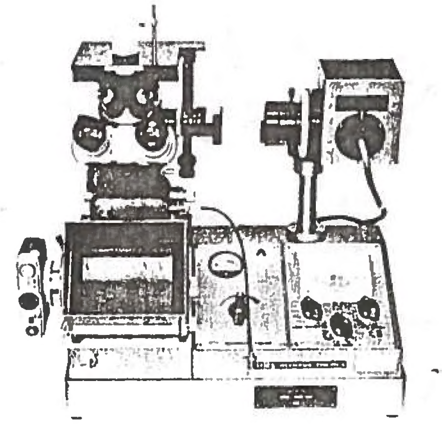


FIGURE 21.19. Metallurgical inverted microscope.

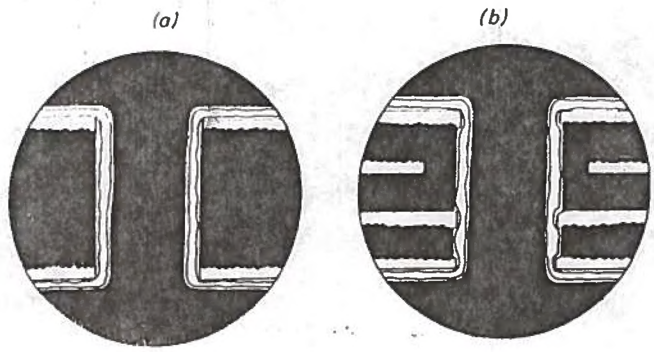
The source of illumination is a tungsten filament lamp whose intensity is controlled by an internal power source. Filters are also available to enhance various aspects of the viewed sample. The microscope shown in Fig. 21.19 has provisions for mounting 35-mm as well as Polaroid cameras and has built-in exposure and color temperature capabilities. In addition, it also has a large-format viewer which enables the magnified image to be inspected on a translucent glass plate.

Specimen Evaluation. Examination of the specimen typically begins with a low magnification, such as 50×, in order to view the overall hole appearance and quality of fabrication. If an imperfection is detected or if a plating thickness measurement is to be taken, the sample is then viewed under a magnification of upward of 200×.

A sample may possess a variety of characteristics or conditions which are all subject to interpretation. Because these interpretations are subjective in most cases, they should be made only by experienced personnel to determine the processing causes of observed defects. In evaluating microsections, we will discuss only those major items which are of concern to both the pc board manufacturer and the end user.

A microsection of a properly processed double-sided board is shown in Fig. 21.20a and that of a correctly processed multilayer board is shown in Fig. 21.20b.

FIGURE 21.20. Cross sections of plated-through holes: (a) double-sided; (b) four-layer MLB.



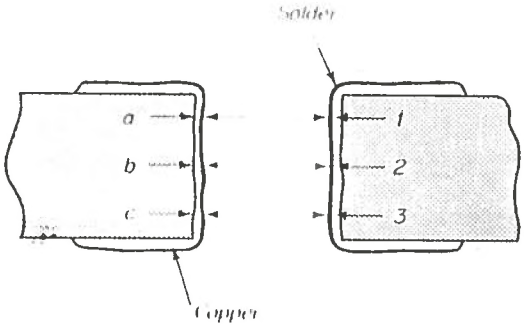


FIGURE 21.21. Three measurement points to determine average plating thickness in a PTH.

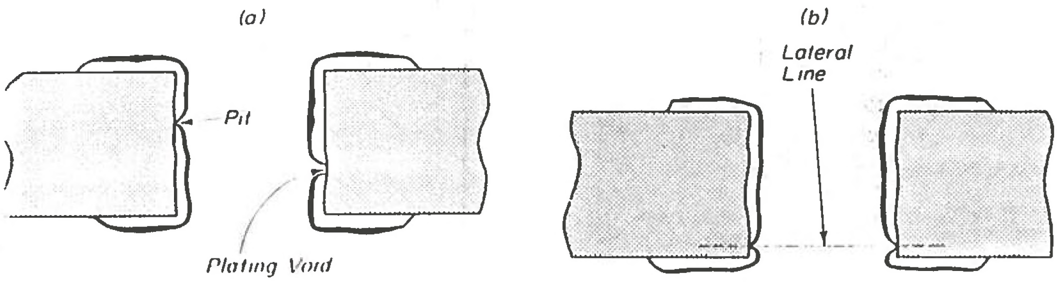
Observe the continuously smooth plated surfaces of both copper and solder with no roughness in the holes caused by drilling or the presence of foreign matter. The overall appearance should be of fine-grained copper having good registration.

Copper and solder thickness measurements inside a plated hole should be made at a minimum of three separate locations within the hole. In Fig. 21.21 copper thickness measurements are taken at points *a*, *b*, and *c*. The results for evaluation are the average of these three readings. Readings of solder plating thickness (measured before reflow) are taken at points 1, 2, and 3 and again averaged.

Voids detected within the barrel are one of the most serious plating problems and, depending on their severity and number, may be subject to criteria for board lot rejection. A void is observed under a microscope as a break or absence in the plating that extends to the laminate base material. Such a void is shown in Fig. 21.22a. When a void appears in approximately the same lateral area of the hole, such as that shown in Fig. 21.22b, it is called a *circumferential* or *rim* void. This defect manifests itself as a break completely around the circumference of the hole resulting in an open circuit between layers. Rim voids are *always* cause for board lot rejection.

Another plating problem that is detectable in microsectioning evaluation is *nodulation*. This is severe plating irregularities or lumps appearing within the plated hole. This defect can result in additional problems, such as plating voids, reduced plating thickness in selected areas of the barrel, and reduced hole diameter. In severe cases, nodulation is cause for lot rejection. Severe nodulation of a plated-through hole is shown in Fig. 21.23.

FIGURE 21.22. Plating defects found in microsections: (a) plating pit and void; (b) rim void or circumferential void.



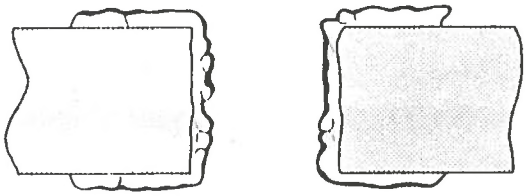


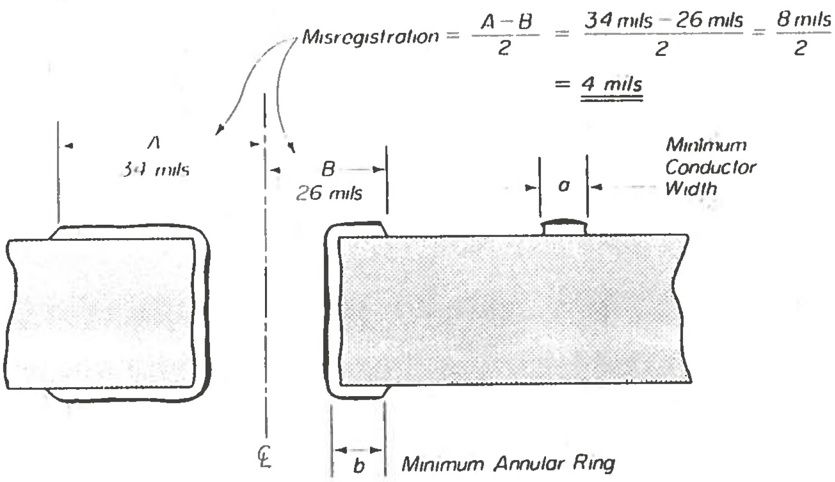
FIGURE 21.23. Severe plating irregularity, termed nodulation.

Other measurements that can be easily made on a microsectioned sample are the minimum conductor width and the annular ring (see Fig. 21.24). The minimum conductor width measurement is shown as dimension *a*. It is a determination of the amount of undercutting which resulted from the fabrication processes. The measurement of annular ring is shown in Fig. 21.24 as dimension *b*. These measurements will detect both registration and processing problems which may exist.

For multilayer boards, inner-layer registration is extremely critical and also can be determined on a microsectioned sample. A multilayer board with a severely misregistered inner layer is shown in Fig. 21.25. The amount of misregistration is found by first locating the center line (C_L) of the hole. Dimensions *A* and *B* are then measured from this center line. Dividing the difference between dimensions *A* and *B* by 2 will yield the amount of misregistration of the inner-layer pad.

Another defect of plated-through holes in multilayer boards is known as *epoxy smear*. This is the result of excessive heat generated in the drilling process, which causes the epoxy in the laminate to melt during drill penetration. When the drill is removed, it causes the epoxy to smear over the interface area of copper and laminate. This results in an insulated area formed between the inner-layer copper and the plated barrel. Epoxy smear is detectable on the microsectioned sample and can be removed with the use of chemicals as discussed in Chapter 20. A multilayer board with epoxy smear on an inner layer is shown in Fig. 21.26.

FIGURE 21.24. Measurements made on a microsectioned PTH.



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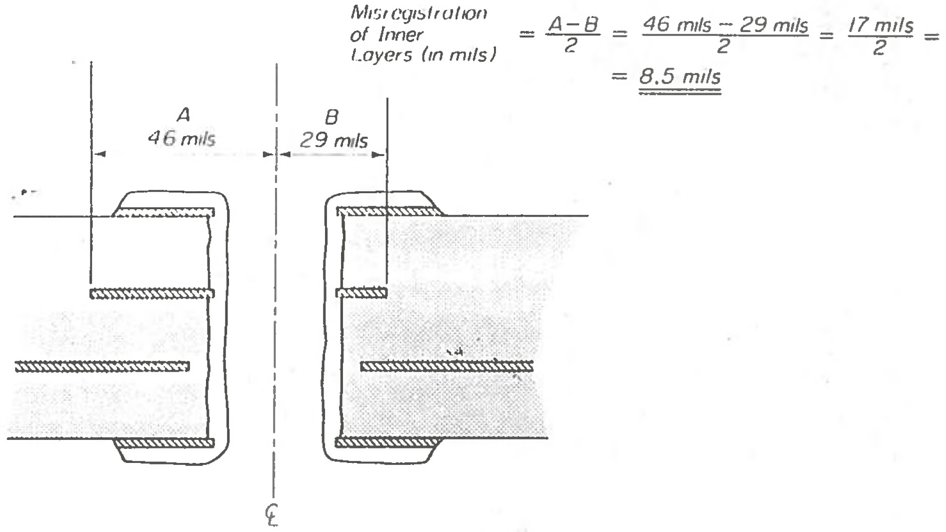

FIGURE 21.25. MLB inner-layer misregistration measurement.

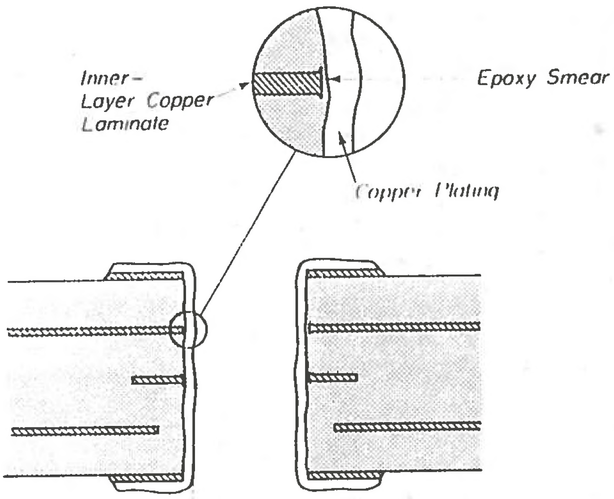

FIGURE 21.26. Epoxy smear detected in microsection shows open-circuit defect.

Etchback is a chemical process used in the manufacture of multilayer boards. Its purpose is to remove a small amount of insulating material between inner layers before the holes are plated. This insulation removal provides a footing in order to obtain a reliable interconnection. Etchback is specified with a minimum and maximum number which ranges from 0.0002 to 0.003 inch, with typical ranges of 0.001 to 0.003 inch. If the amount of insulating material removed is insufficient, proper footing will not be achieved. On the other hand, an excessive amount removed will result in rough hole wall plating (see Fig. 21.27).